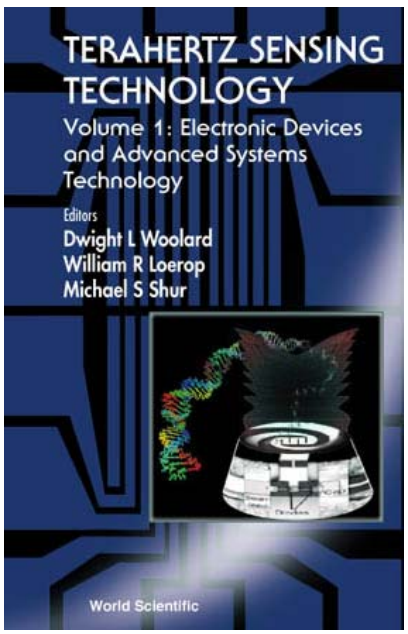
Terahertz Sensing Technology

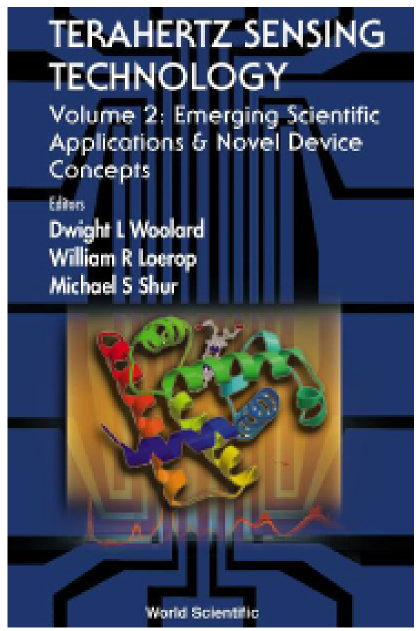
Michael Shur

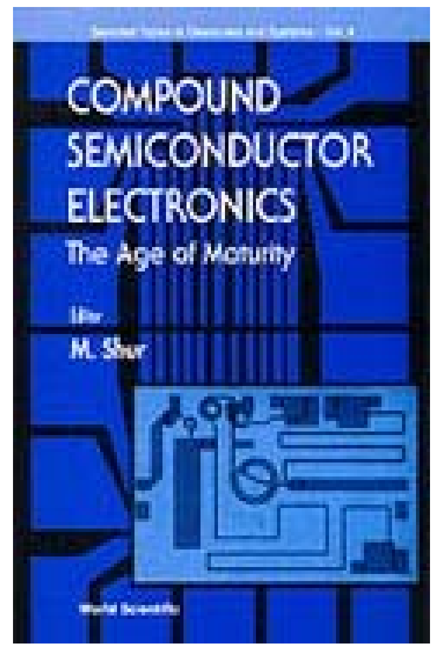
CIE, ECSE, Physics, and Center for THz Research

Rensselaer Polytechnic Institute

http://nina.ecse.rpi.edu







IEEE Sensors Conference October, 2008

I am grateful to my THz colleagues for their hard work, inspiration, and contributions


Dr. Dyakonova and Prof. Dyakonov


Dr. Veksler


Dr. Kachorovskii


Prof.Pala


Dr. Knap


Dr. Rumyantsev


Dr.Deng

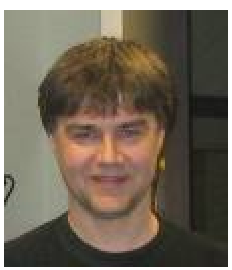

Prof. M. Ryzhii

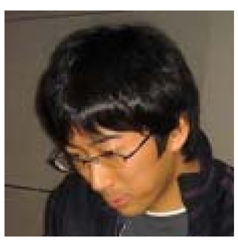

Dr. Dmitriev


Prof. Zhang

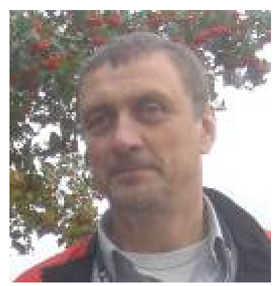

Prof. V. Ryzhii


Dr. Stillman


Dr. Muraviev


Dr. Satou

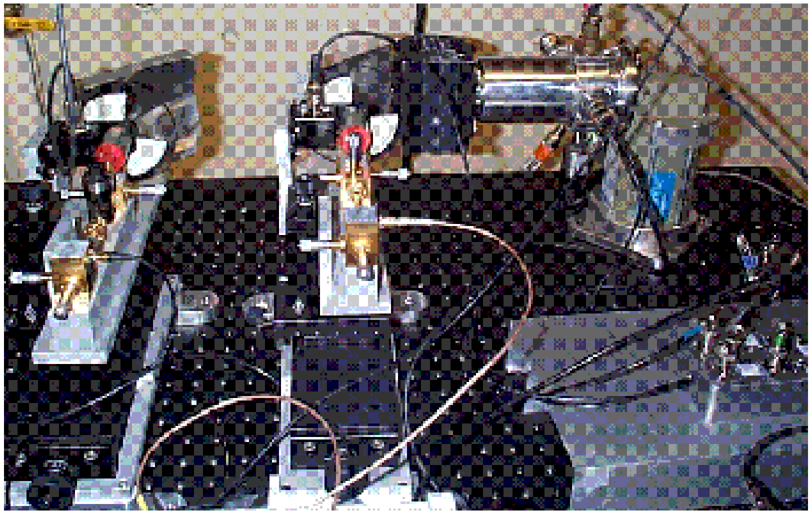

Dr. Levinshtein


Dr. Popov


THz Center at RPI led by Prof. Zhang

Tutorial Outline

- History
- Applications
- Terahertz Photonics
- Terahertz Electronics
- Plasma wave electronics
- Terahertz properties of grainy multifunctional materials
- Conclusions and future work



Tutorial Outline

History

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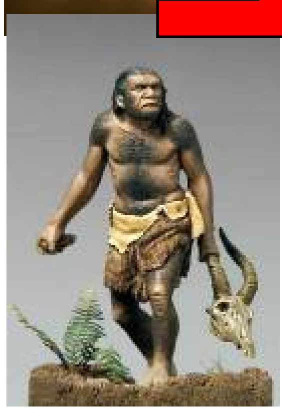
From http://www.phys.uu.nl/~vgent/astronomia_large.jpg

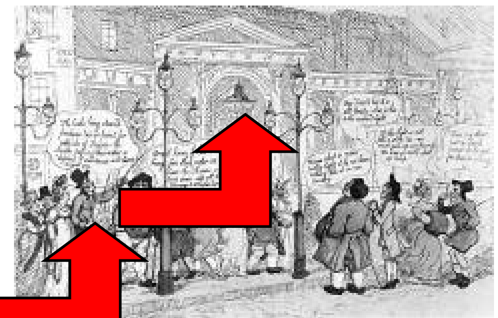
Human Civilization and Electromagnetic Spectrum
Visible Spectrum



From using Sun

To the first torch 500,000 years ago

To the first candle 1,000 BC

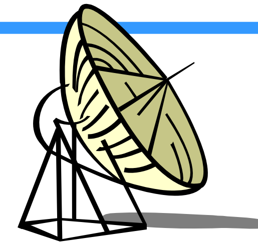


To gas lighting 1772

To Edison bulb 1879

Soon to be replaced by LEDs
Solid State Lighting

Moving to shorter and longer wavelengths in the 19-th and 20-th century



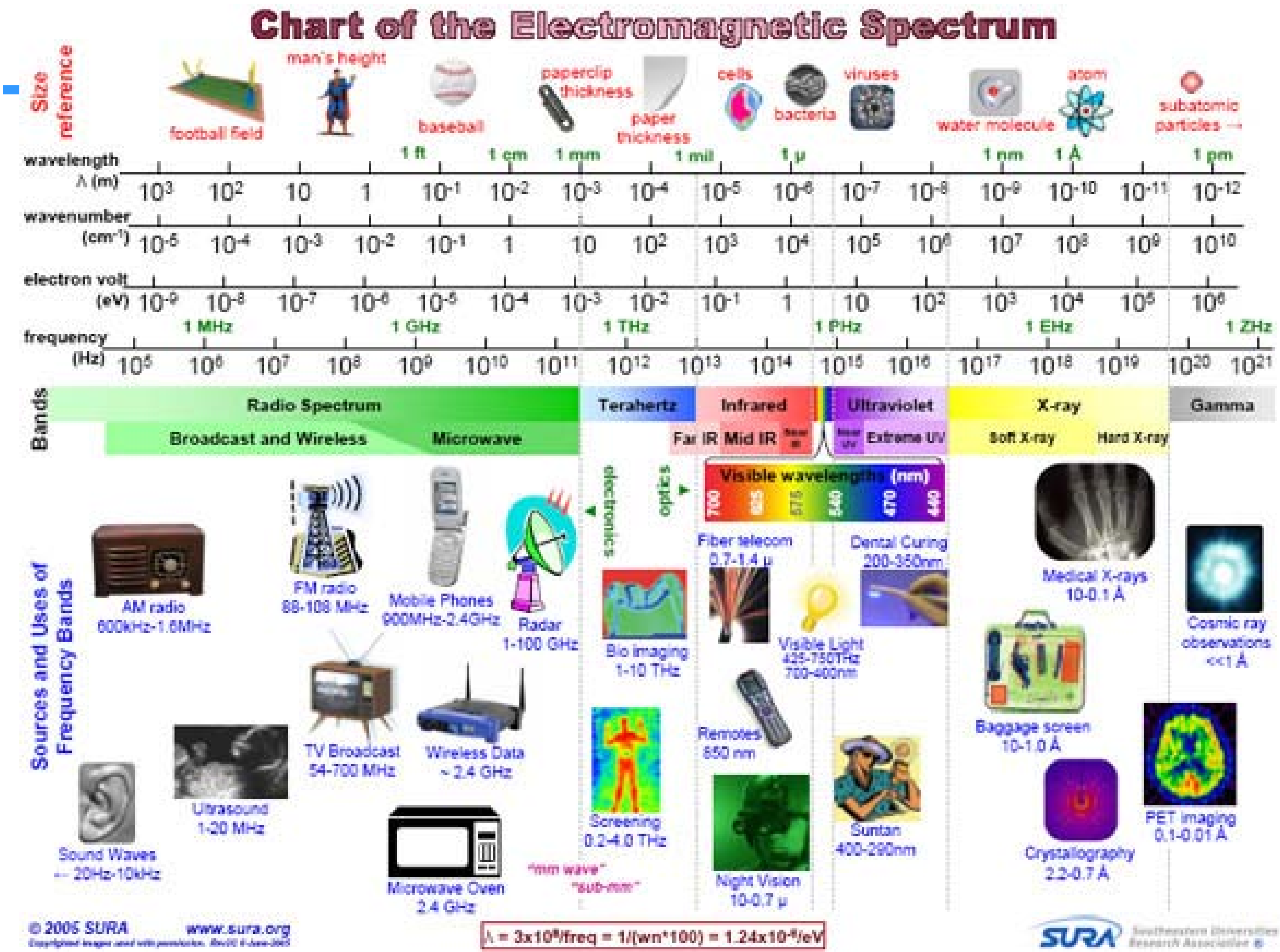
- Radio 1 – 10^8 m (1936)
- Radar 10^{-1} – 1 m (1936) Cell phone (1973)

- **<u>Terahertz Gap (10 μm – 1 mm)</u>**
- IR

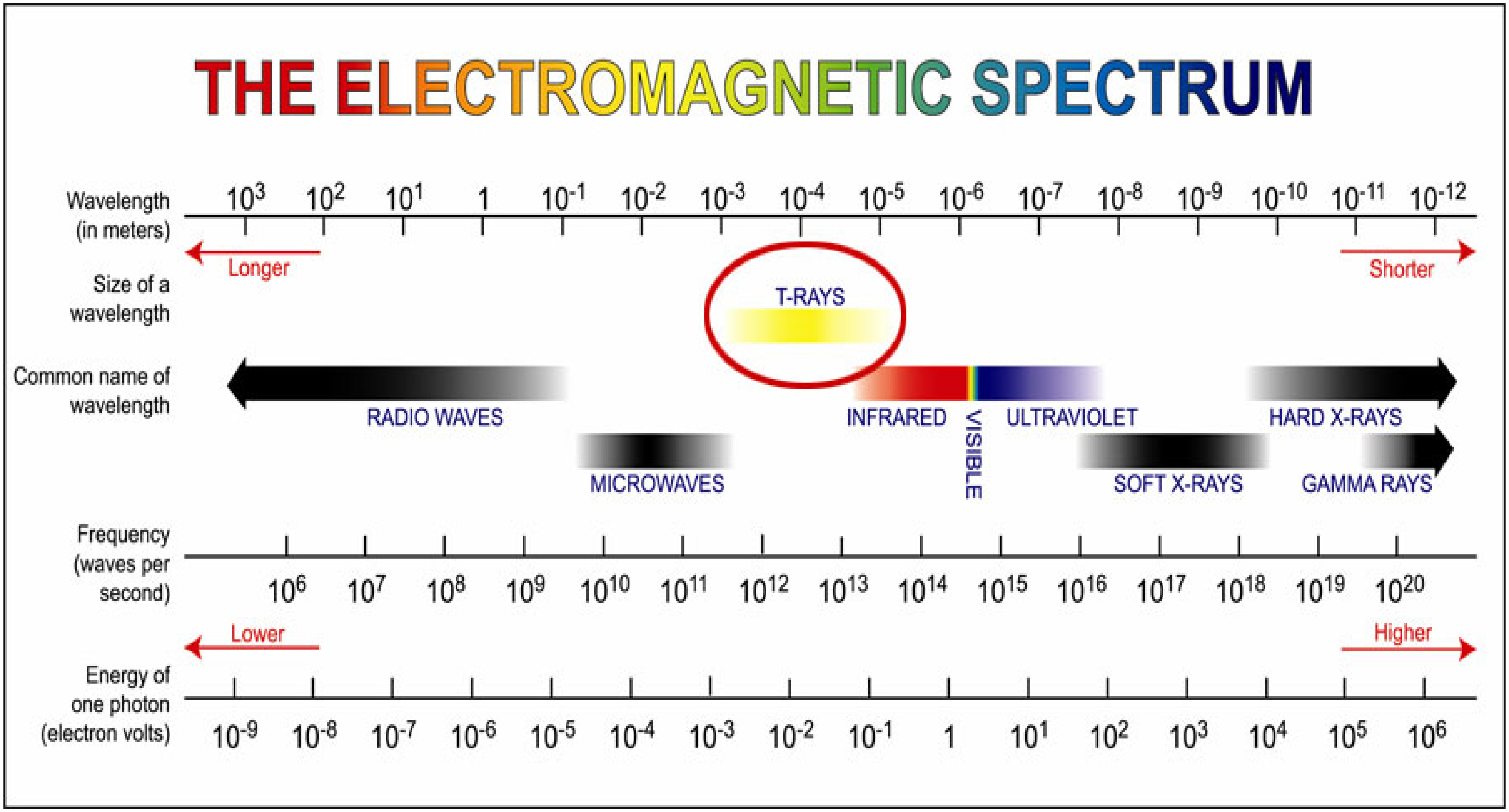
- Incandescent 4 10^{-7} – 7.6 10^{-7} m (1901) LEDs (1961)
- UV 10^{-7} – 4 10^{-7} m (1901)

- X-ray 10^{-14} – 10^{-7} m (1895)

From tryshotcode.com/terahertz1.aspx



T-rays



From: http://www.advancedphotonix.com/ap_products/images/prods_Terahertz_graphLarge.jpg

Synonyms

- *Big and large*
- *buy* and *purchase* (verb)
- Car and automobile
- **THz, submillimeter and far-infrared**

- **1 THz -> 300 μm -> 4.3 meV ->33 cm^{-1}**

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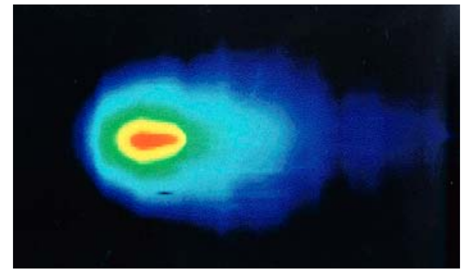
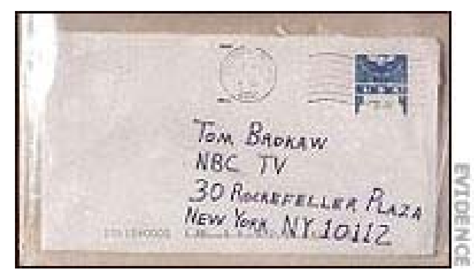
- Plasma wave electronics
- Terahertz properties of grainy multifunctional materials
- Carbon THz electronics and photonics
- Conclusions and future work



Comet Iras-Araki-Alcock. Image is taken at 12 THz

Courtesy of Infrared Processing and Analysis Center, Caltech/JPL. IPAC is NASA's Infrared Astrophysics Data Center

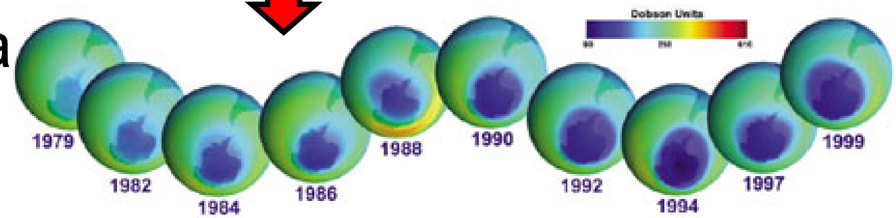


From : www.burbankwire.com/fbi_advisory.shtml

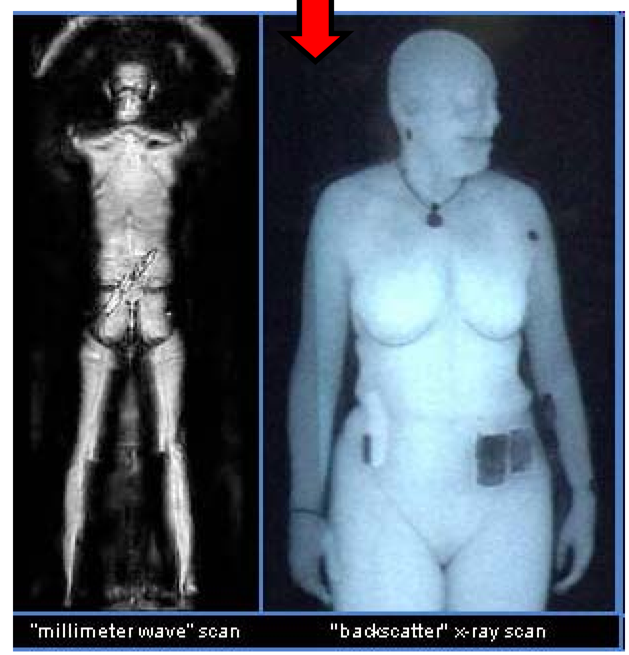
THz Applications

- Radio astronomy
- Earth remote sensing
- Vehicle radars and compact ra
- Non-destructive testing
- Chemical analysis
- Explosive detection
- Moisture content determination
- Coating thickness control
- Imaging
- Film uniformity
- Structural integrity
- Wireless covert communications
- Medical applications
- Concealed weapons detection

http://science.hq.nasa.gov/missions/satellite_22.htm



From http://24hoursnews.blogspot.com/2007_09_24_archive.html



Privacy Concerns?

- The machine creates a 3-d image of the passenger's body then sends it to a viewing station in another room where a TSA agent looks for potential threats.
- "It's passenger imaging technology, so it allows us to see the entire image of the passenger's body and anything that might be hidden on the person" said Ellen Howe of TSA.
- The new technology includes new privacy protection also. The screener in the viewing room can't see the passenger's face and the images from the machine are deleted, once the traveler is cleared to fly.

From http://24hoursnews.blogspot.com/2007_09_24_archive.html

IRAM interferometer (Plateau de Bure, French Alps)

From *Pierre ENCRENAZ & Gérard BEAUDIN* Recent developments in millimeter and submillimeter waves. http://gemo.obspm.fr/ArticleLigne/RecentDvlp.html

- Started in 1985
- 6 antennas of 15 meters diameter
- Wavelength of 1.3 mm (230 GHz)
- Antennas of the IRAM interferometer can move on rail tracks up to a maximum separation of 408 m in the E-W direction and 232 m in the N-S direction
- Resolution of 0.5 arcsecs (resolving an apple at a distance of 30 km).

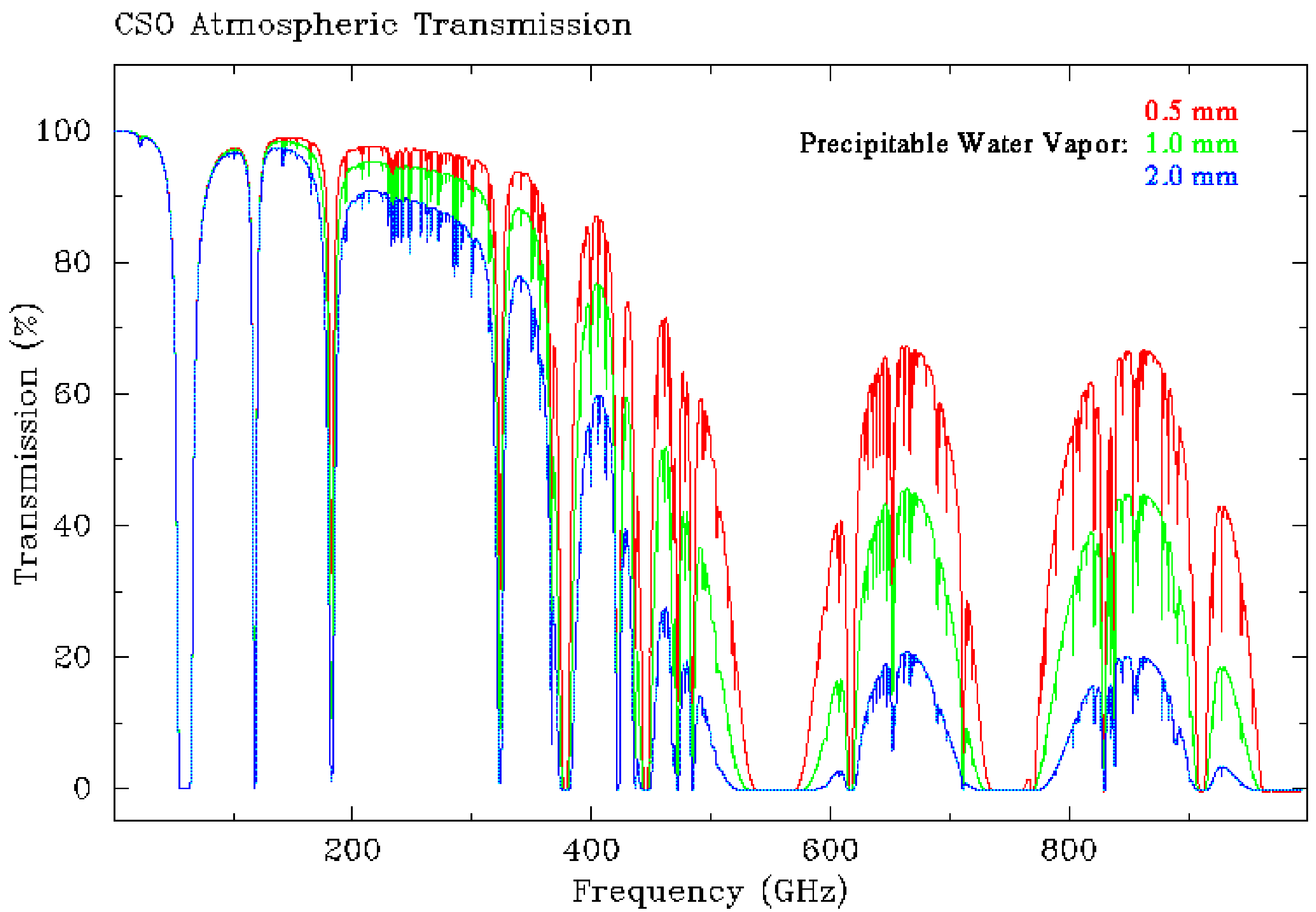
CONDOR (1.5 THz heterodyne receiver) at APEX (Atacama Pathfinder EXperiment) in Chilean Andes

Detected hot gas in the vicinity of young massive stars. The THz atmospheric windows centered at 1.3 and 1.5~THz contain spectral lines of including CO lines, the N+ line at 205 microns, and the ground transition of para-H2D+.

11/2005

http://www.sciencedaily.com/images/2005/12/051227155401.jpg

Why THz telescope is in Chile



From www.submm.caltech.edu/cso/cso_submm.html

Stratospheric Observatory For Infrared Astronomy (SOFIA). Using CONDOR on SOFIA.

747 airplane with an infrared telescope inside

From http://www.etsu.edu/physics/bsmith/variable/sofia.gif

THz detects cold matter (140 K or less), such as clouds of gas and dust in our and nearby galaxies. New stars beginning to form radiate heat as they contract and are clearly seen in the THz range. Stars invisible in a dense cloud of dust appear as very bright stripe in the THz image because they heat the dust that glows in far-infrared

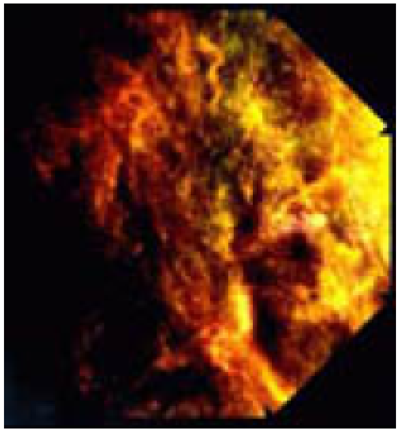


Figure 3a. Infra Red Astronomical Satellite (IRAS) view of dust heated by starlight (from [5])

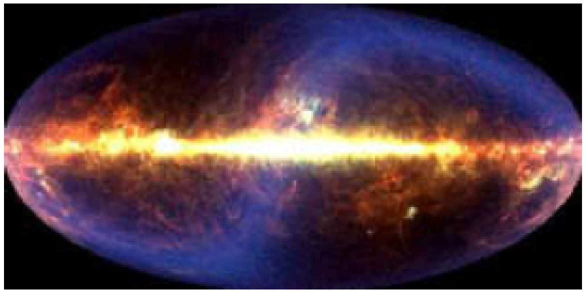
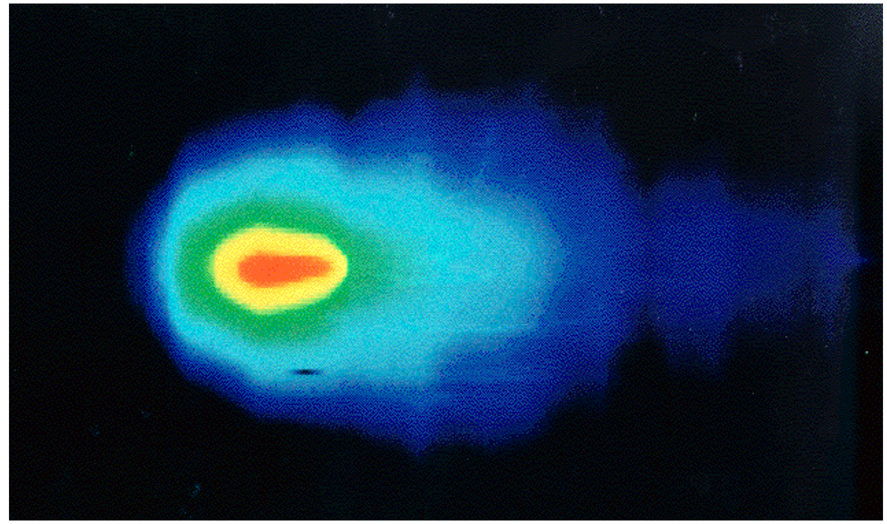


Figure 3b. Image taken by the COBE satellite is a composite of THz wavelengths of 60, 100, and 240 microns. (from [6], photo: Michael Hauser (Space Telescope Science Institute), the COBE/DIRBE Science Team, and NASA).

[5] http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/images/iras_cirrus.jpg
[6] http://www.esa.int/esaSC/Pr_1_2002_s_en.html

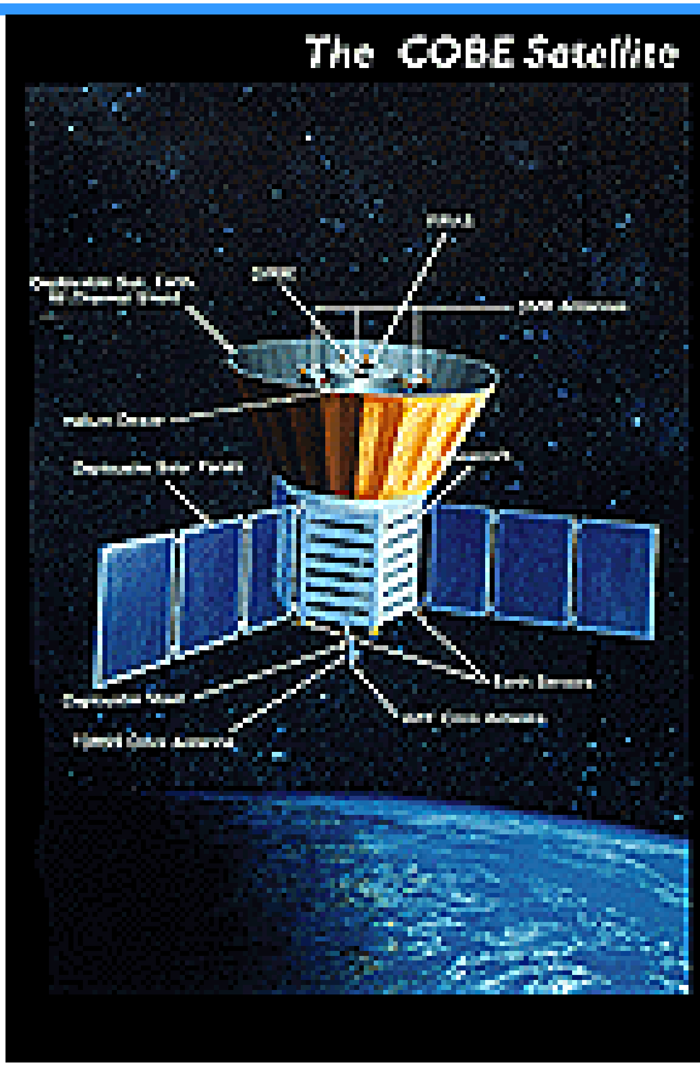
Infrared Astronomical Satellite (IRAS) in its 560-mile-high, near-polar orbit above the Earth



Comet Iras-Araki-Alcock was discovered by (IRAS). Image is taken at 25 micron (12 THz)

Courtesy of Infrared Processing and Analysis Center, Caltech/JPL. IPAC is NASA's Infrared Astrophysics Data Center

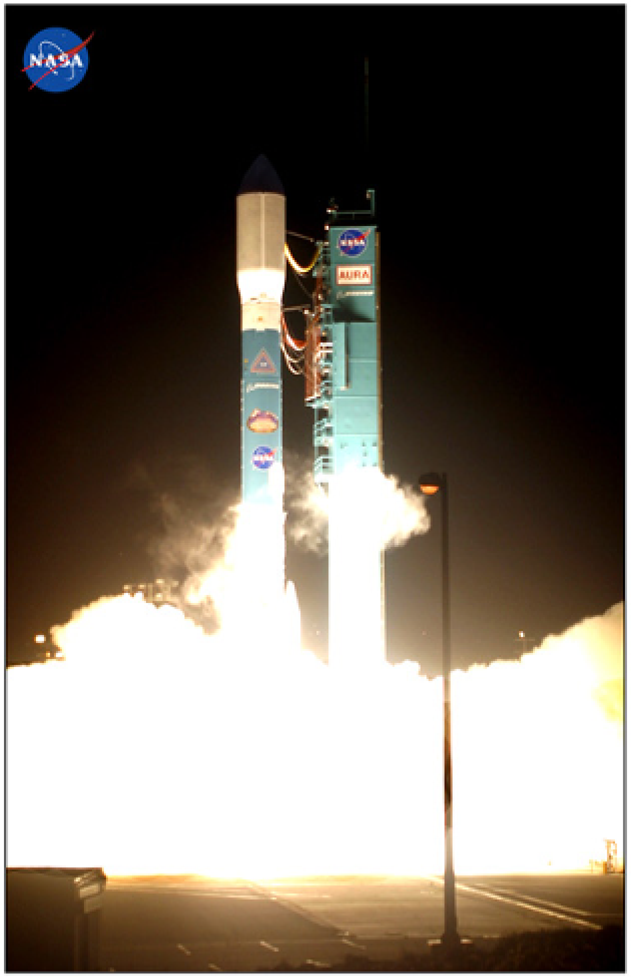
COBE – Cosmic Background Explorer



- **<u>Far Infrared Absolute Spectrophotometer (FIRAS)</u> measuring the spectrum of cosmic microwave background radiation (CMBR)**
- **<u>Differential Microwave Radiometers (DMR)</u> detecting faint fluctuations in CMBR**
- **<u>Diffuse Infrared Background Experiment</u> (DIRBE) obtaining data on cosmic infrared background, structure of Milky Way and interstellar dust.**

From http://lambda.gsfc.nasa.gov/product/cobe/slide_captions.cfm

Aura spacecraft: Earth Atmosphere Monitoring



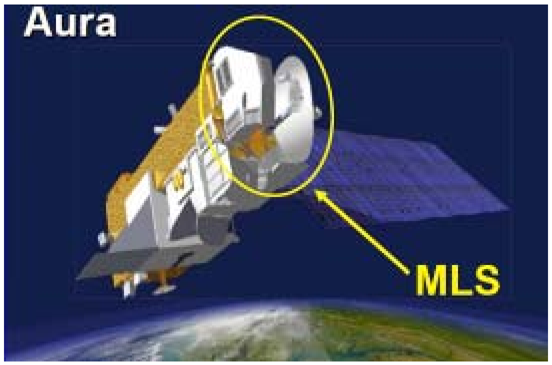
Aura Launch : July 15, 2004
Vandenberg Air Force Base, CA
EOS

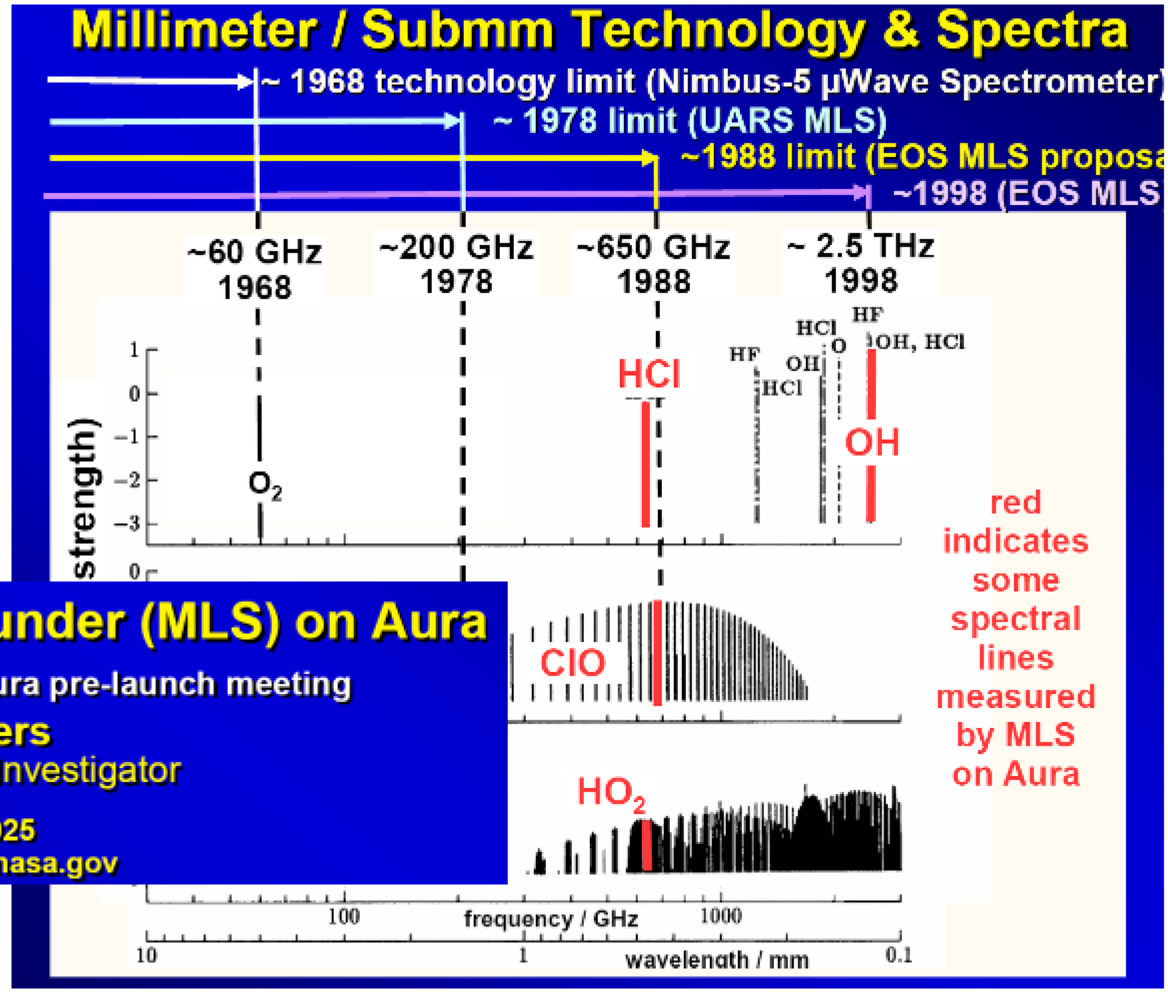
- The Aura spacecraft was launched into a near polar, sun-synchronous orbit with a period of approximately 100 minutes. The spacecraft repeats its ground track every 16 days to provide atmospheric measurements over virtually every point on the Earth in a repeatable pattern, permitting assessment of atmospheric phenomena changes in the same geographic locations throughout the life of the mission.

From http://aura.gsfc.nasa.gov/spacecraft/index.html

Microwave Limb Sounder

From http://mls.jpl.nasa.gov/joe/Aura_pre-launch_MLS_9-charts.pdf





The Microwave Limb Sounder (MLS) on Aura

presentation at 8 July 2004 Aura pre-launch meeting

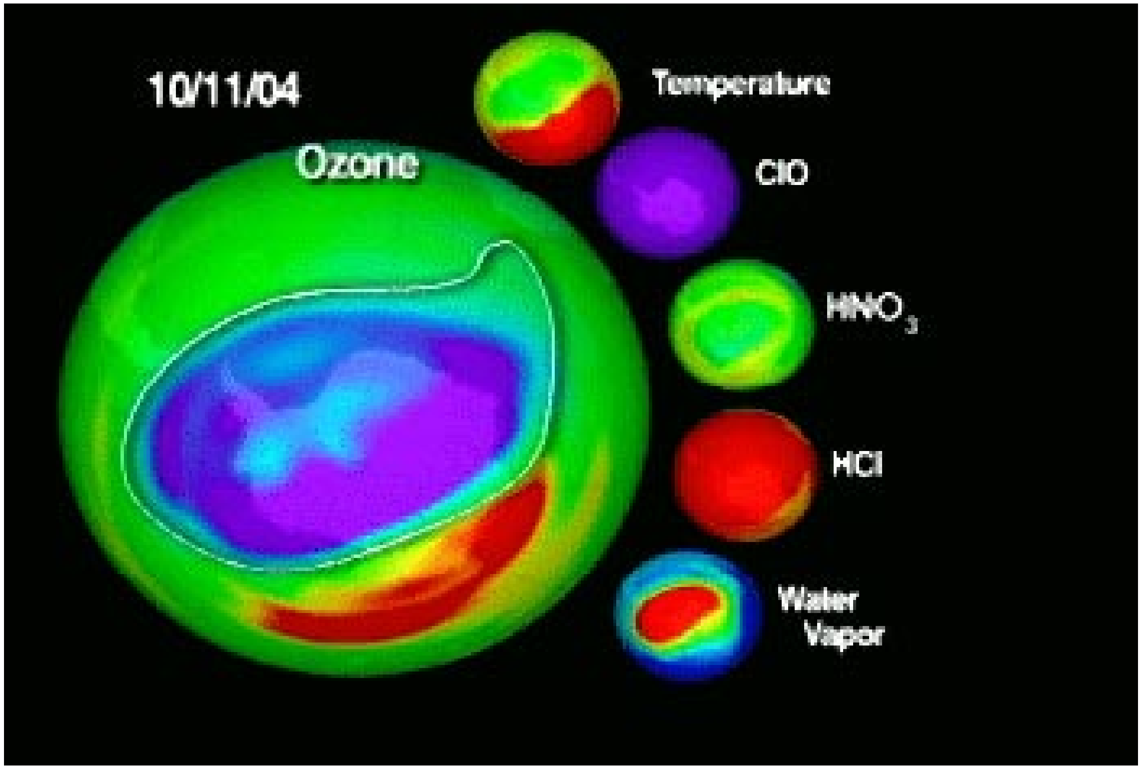
Joe Waters

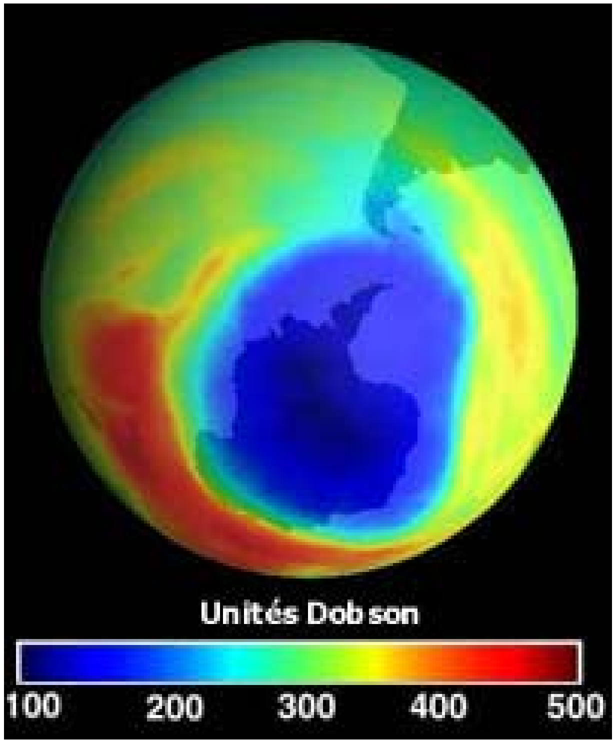
MLS Principal Investigator

818-354-3025

joe@mls.jpl.nasa.gov

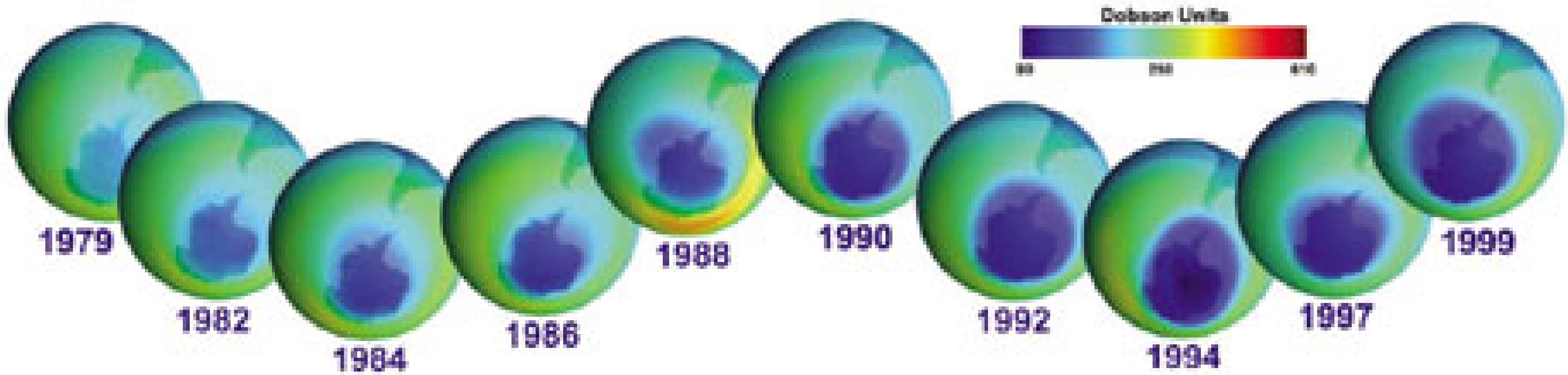
Environmental Control: Ozone Hole





From: http://www.jpl.nasa.gov/news/news.cfm?release=2004-291

Development of Ozone Hole



http://science.hq.nasa.gov/missions/satellite_22.htm

One out of five Americans will develop cancer over their lifetime

Vehicle Radar

From http://www.ntu.edu.sg/home/eadams/IROS_2005_tutorial/dsta_vehicle+radar.JPG

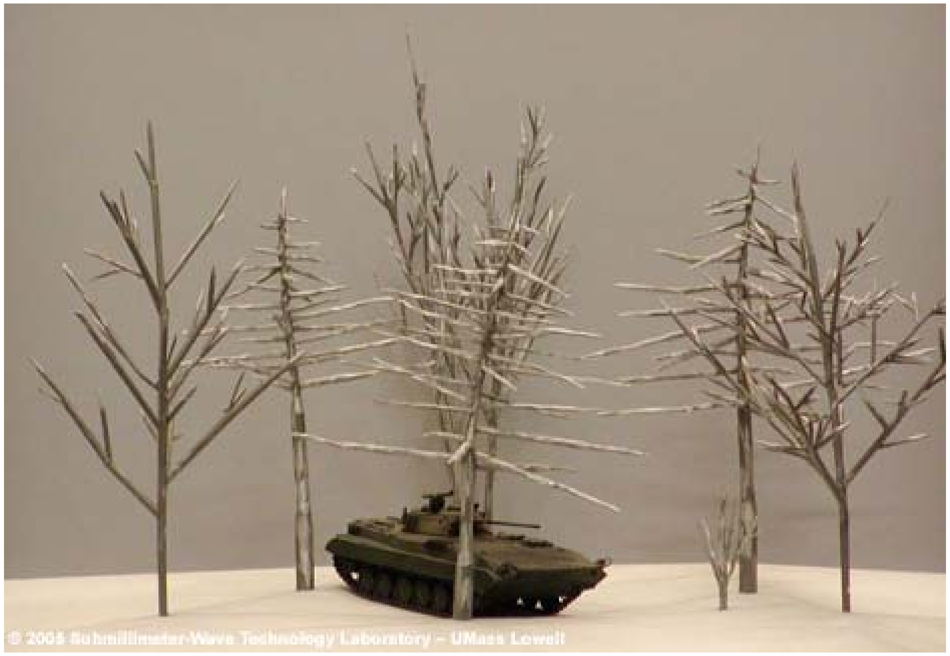
From http://www.uml.edu/media/enews/print_1_108961_108961.html

http://www.virtualacquisitionshowcase.com/thumbs/vas_323.jpg

Compact Radar Range

Tank model

From stl.uml.edu/research/radar.html



stl.uml.edu/research/sub_9.html

Dielectrically scaled trees

Scientific Investigations

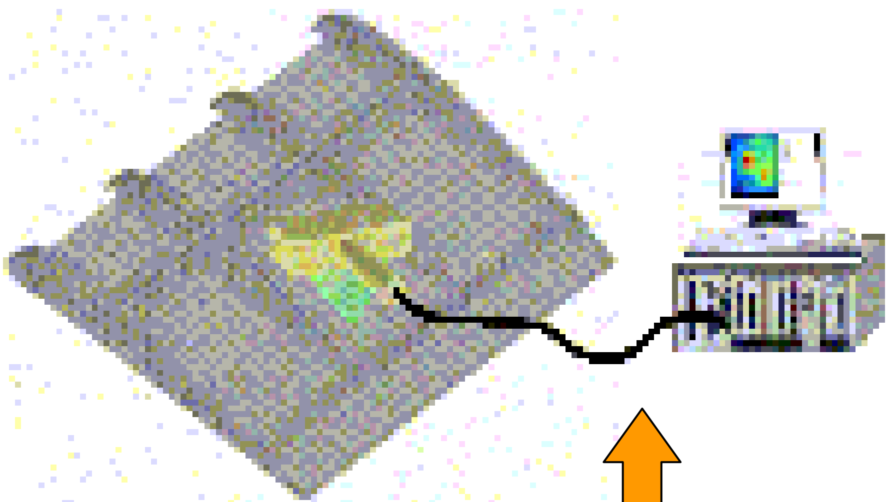
Exploring THz Spectroscopy:
Technology and applications in the field of dynamics and nanostructures

International Bunsen Discussion Meeting
Bad Honnef, April 1-4, 2007

W. van der Zande (Radbout University, Nijmegen)
A narrow band high intensity light source from 0.3 to 3 THz: a free electron laser
M. Hofmann (Ruhr-Universität Bochum)
Diode laser based THz technology
N. Hiromoto (Shizuoka University, Japan):
Terahertz remote sensing in the living space
D. Leitner (University of Nevada at Reno, USA)
Dynamics and THz absorption of protein hydration water

Non-destructive testing of materials and electronic devices

From: www.navyopportunityforum.com/abstracts.php?on..
Abstract # 20



GMA Industries, Inc.
Terahertz Imaging System for Composite Material Assessment
Composites, non-destructive inspection, defects, foreign object debris, fiberglass, Kevlar, ceramic

Space Shuttle Foam Inspection

- After the Space Shuttle Columbia disaster in 2003, NASA started examining the shuttle fuel tank using the Picometrix QA1000.

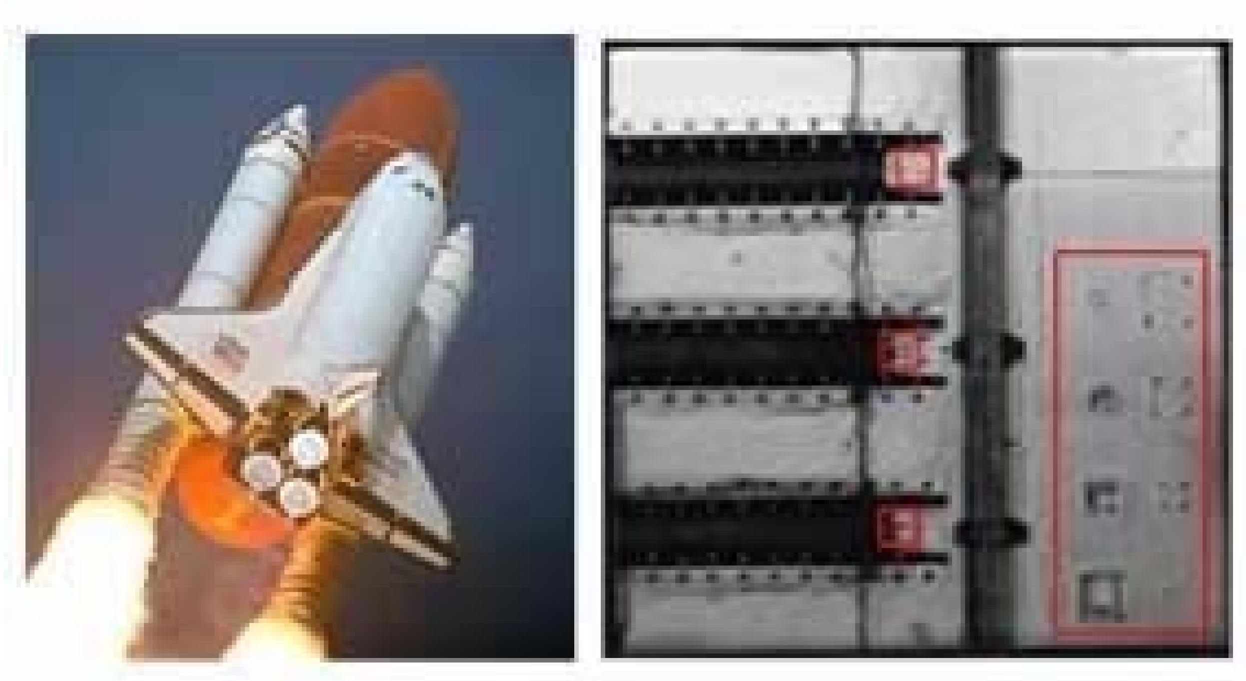


Image from: http://www.advancedphotonix.com/ap_products/thz_app_sofi.asp

Space Shuttle Tile Inspection

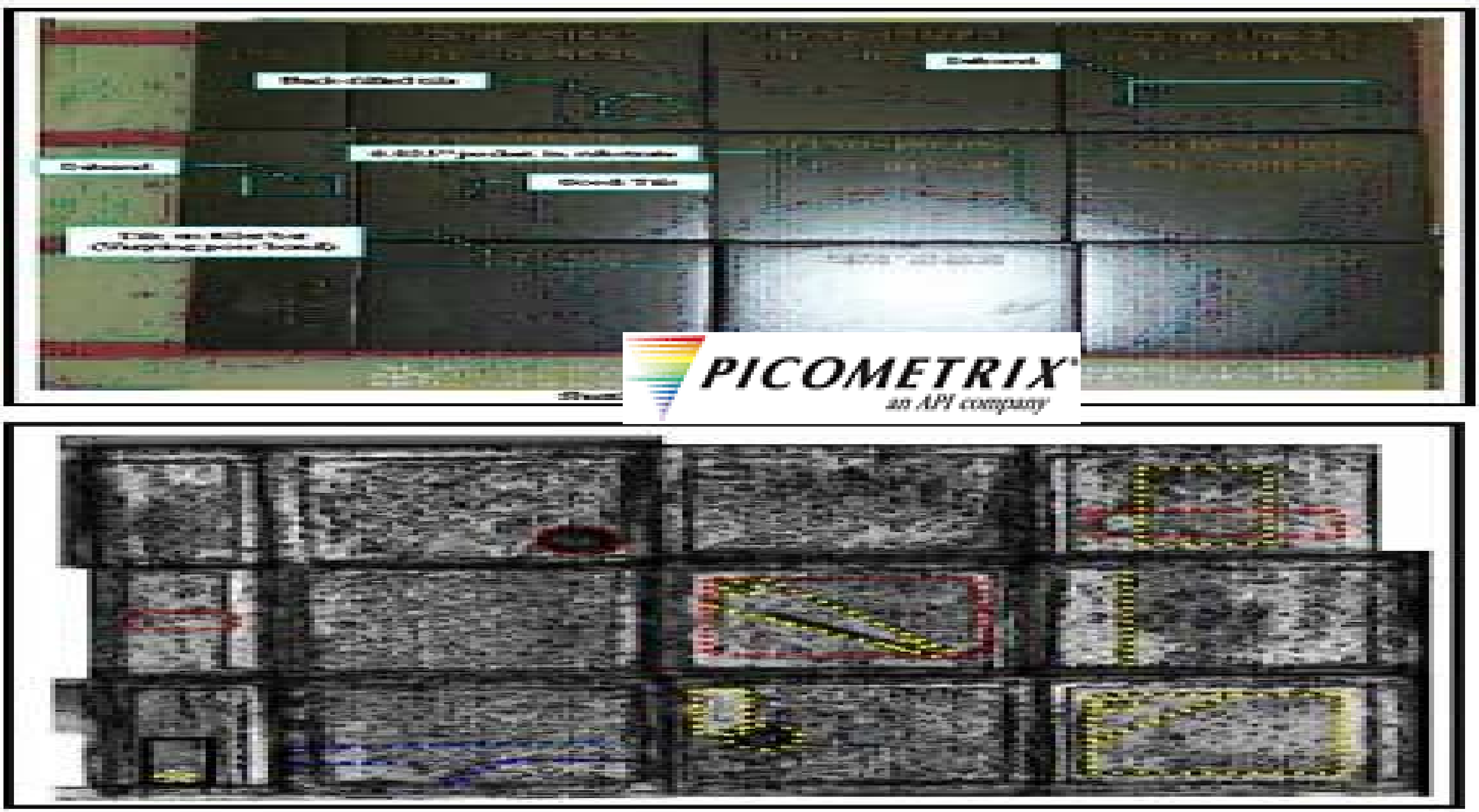
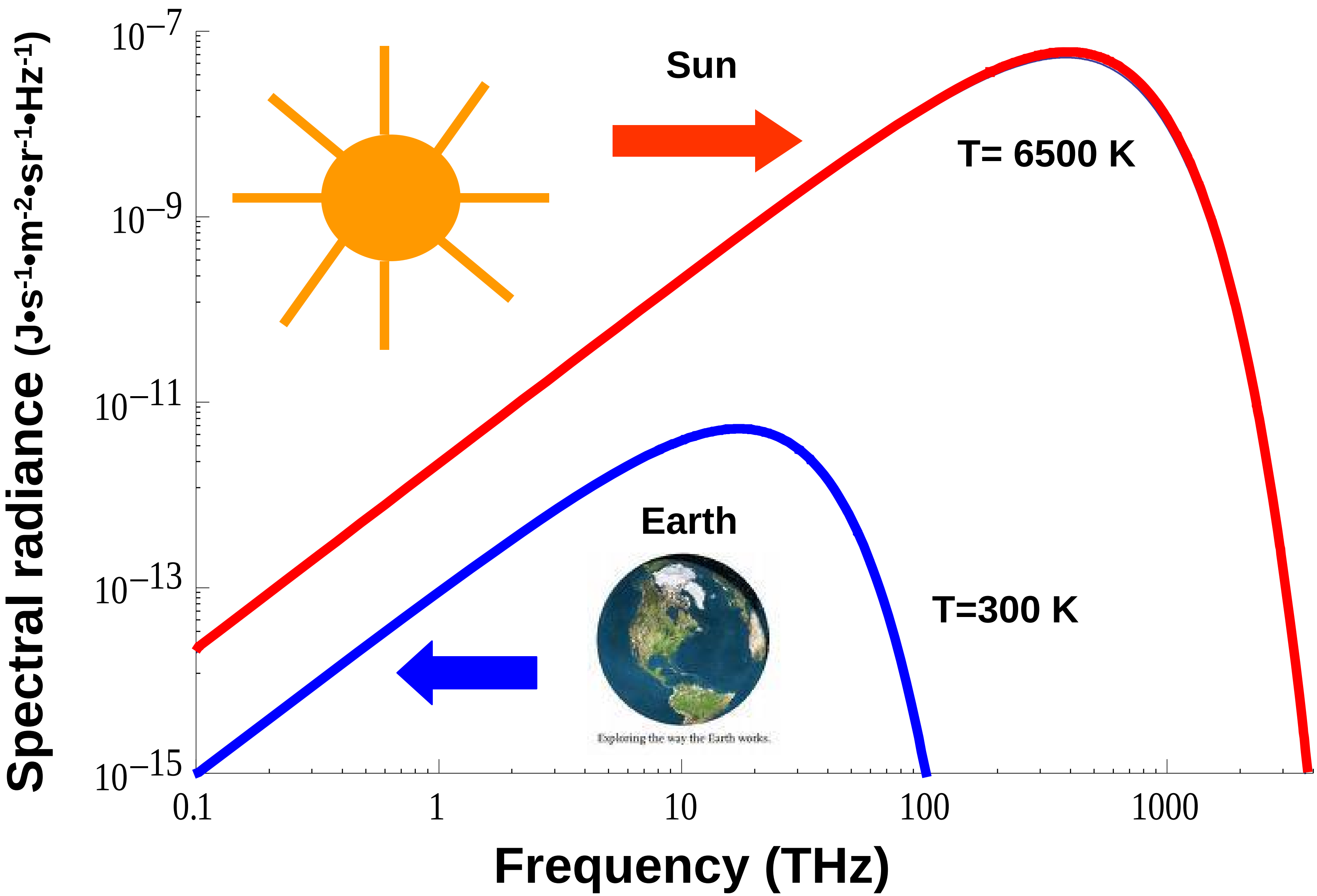
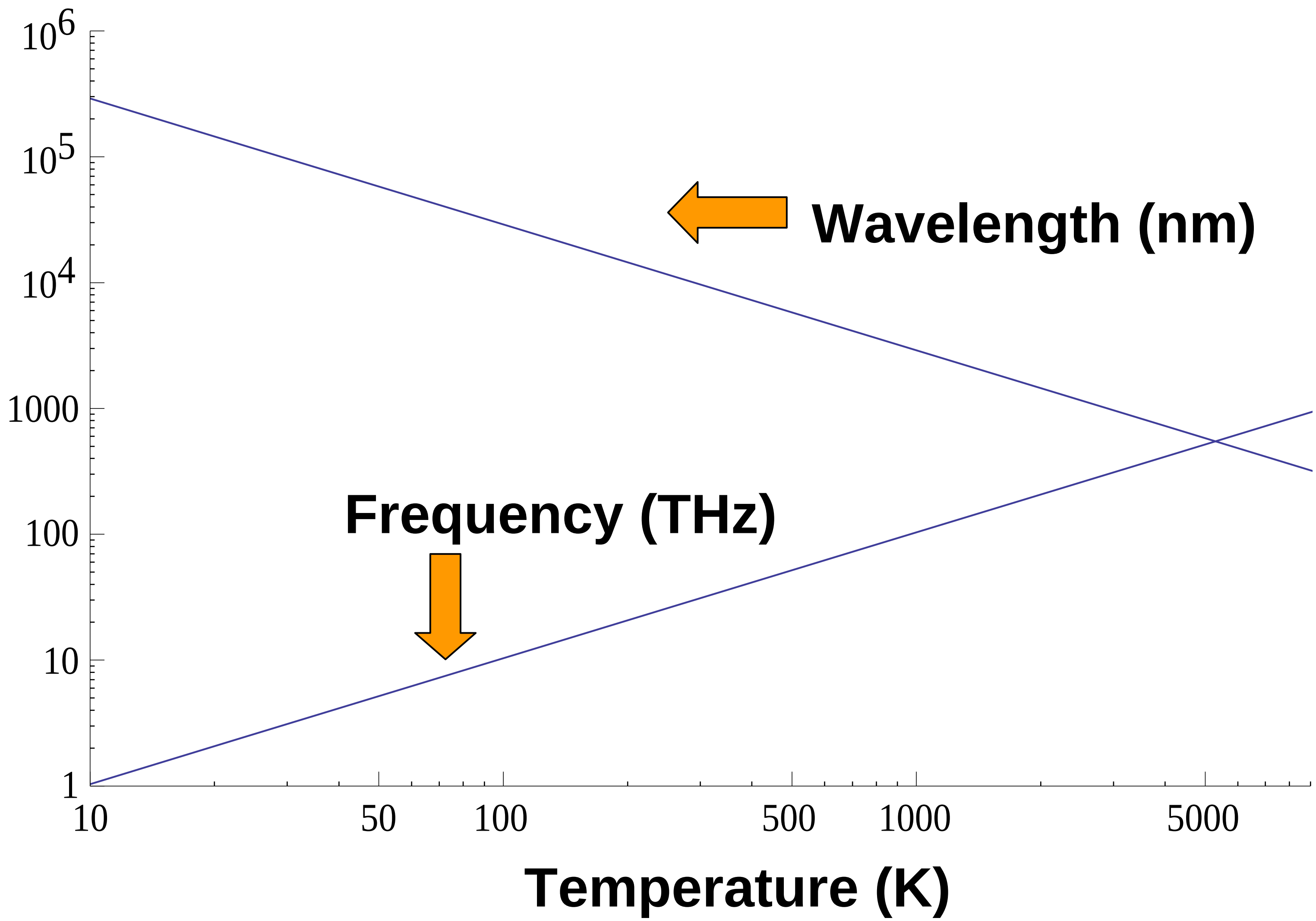


Image from http://www.advancedphotonix.com/ap_products/thz_app_tiles.asp

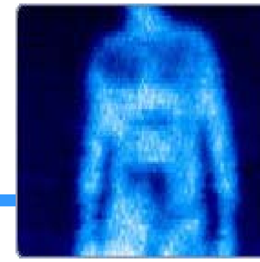
Black Body and THz Radiation



Maximum emission wavelength and frequency



Emissivity



http://www.spectrum.ieee.org/images/jul07/images/tray01.jpg

$$j = \varepsilon \sigma T^4$$

Power per unit area

$$\sigma = \frac{2\pi^5 k^4}{15 c^2 h^3} = 5.670400 \times 10^{-8} \mathrm{J\,s^{-1}m^{-2}K^{-4}}.$$

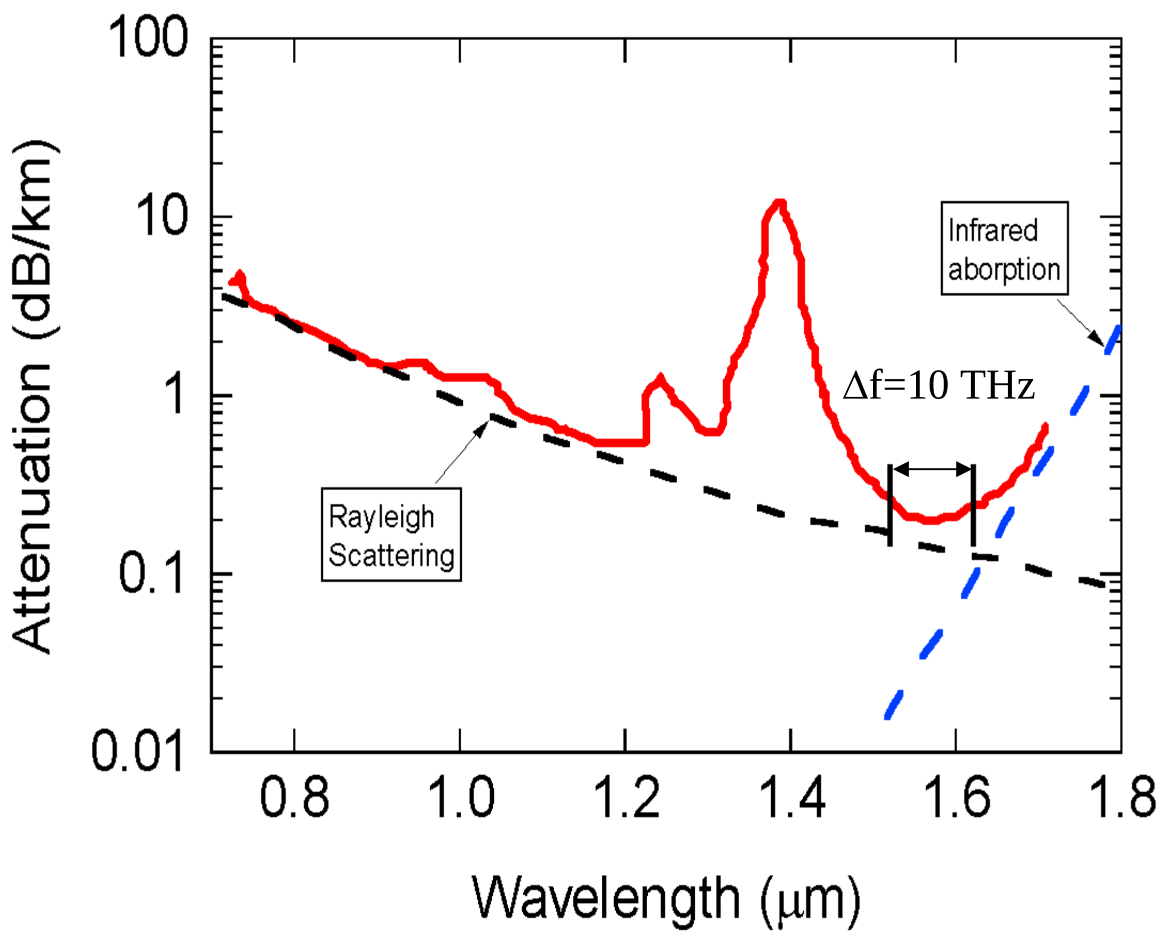
Stefan's constant

Ɛ is emissivity (1 for black body (i.e. for the Sun))

Passive imaging picks up differences in surface temperature and emissivity

Communications: Optical fiber transmission

(Adapted from Streetman, Solid State Electronic Devices)



Diminished Rayleigh Scattering at THz frequencies ($1/\lambda^4$)

Near-field THz microscopy

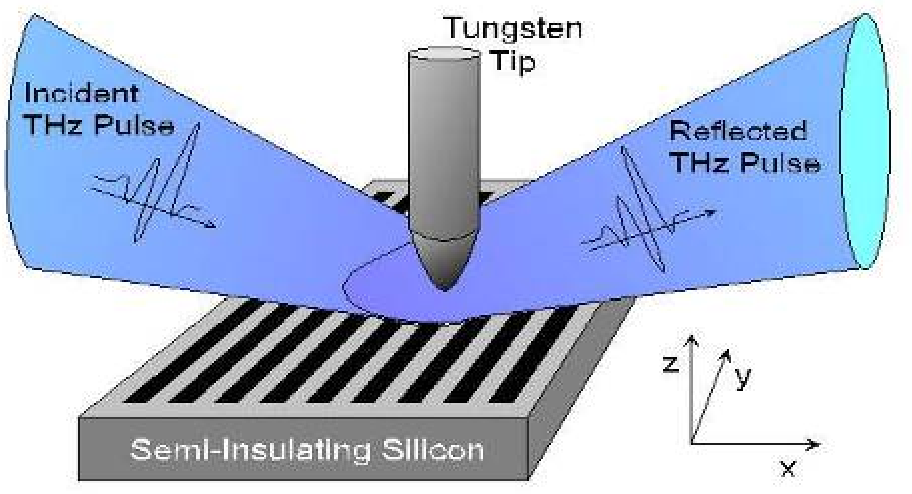
Courtesy Prof. R. Kersting

Challenge: Wavelength of 1 THz: λ = 300 μm

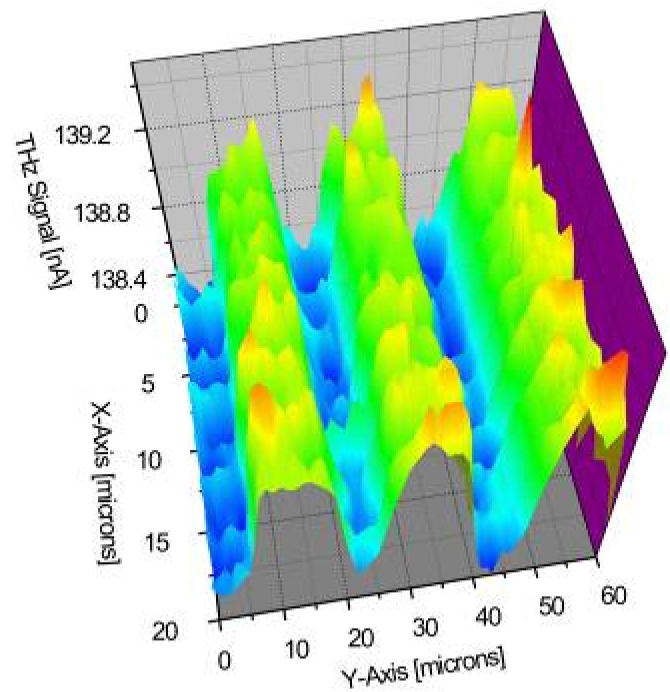
⇨ Scanning Near-field Optical Microscope (SNOM)

Here: Detection of specularly reflected light

Metal grating:



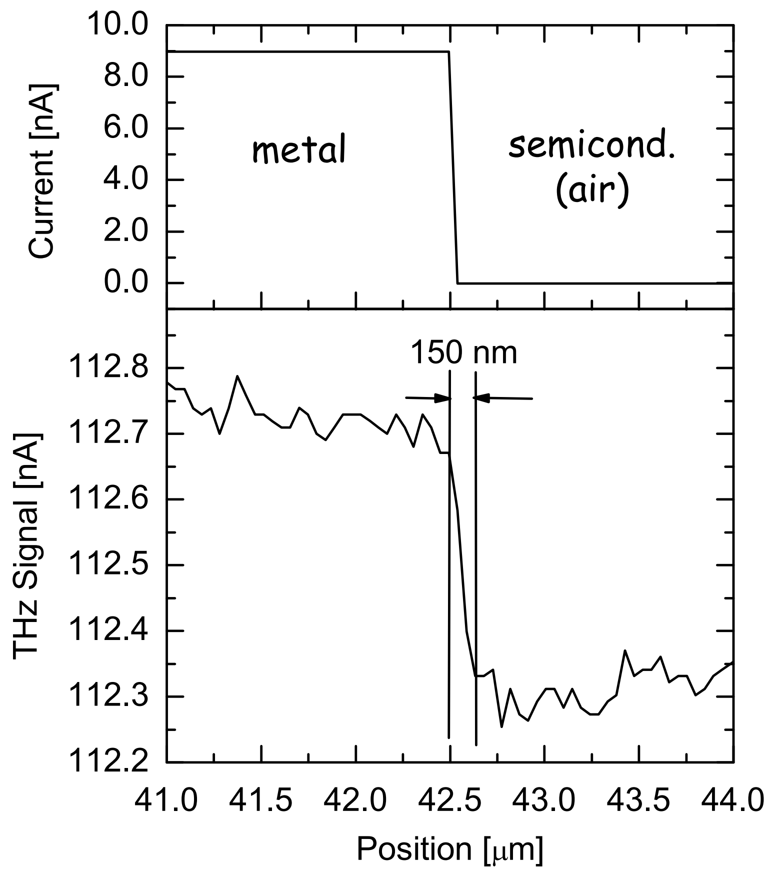
H.-T. Chen, G.C. Cho, and R. Kersting. Appl. Phys. Lett. **83**, 3009 (2003).



Spatial Resolution

Courtesy Professor R. Kersting

Edge mapped at constant height:



Results:

- achieveable resolution: 150 nm (with a 100 nm tip)

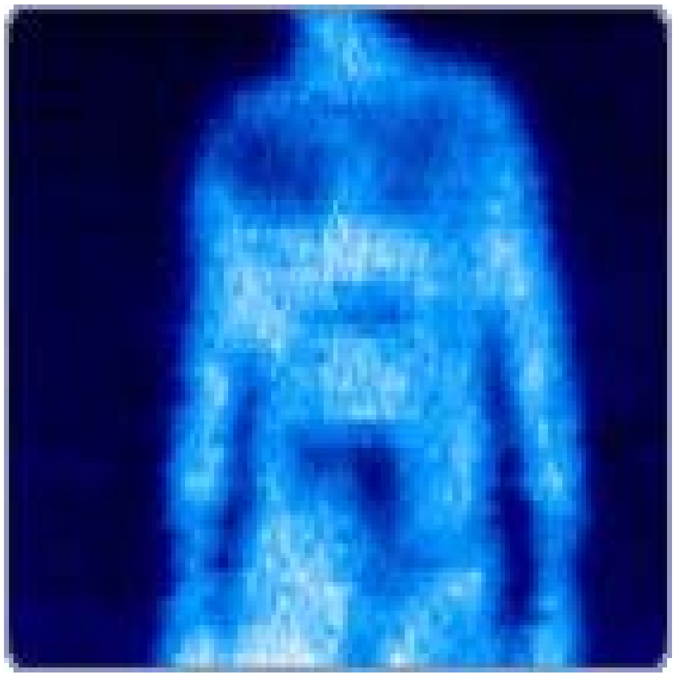
But:

- unexpected high image contrast (> 10^{-3})
- unexpected image polarity

H.-T. Chen, G.C. Cho, and R. Kersting. Appl. Phys. Lett. **83**, 3009 (2003).

Concealed Weapon Detection

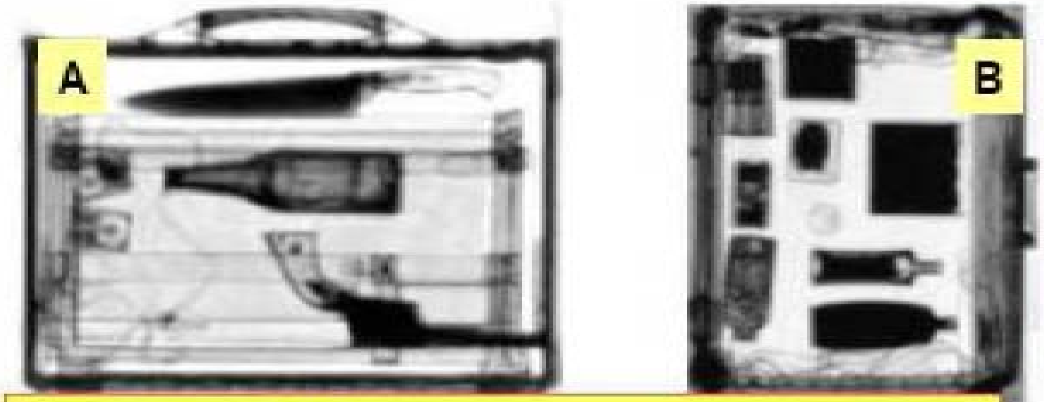
THz Image of a Man Carrying a Gun



http://www.spectrum.ieee.org/images/jul07/images/tray01.jpg

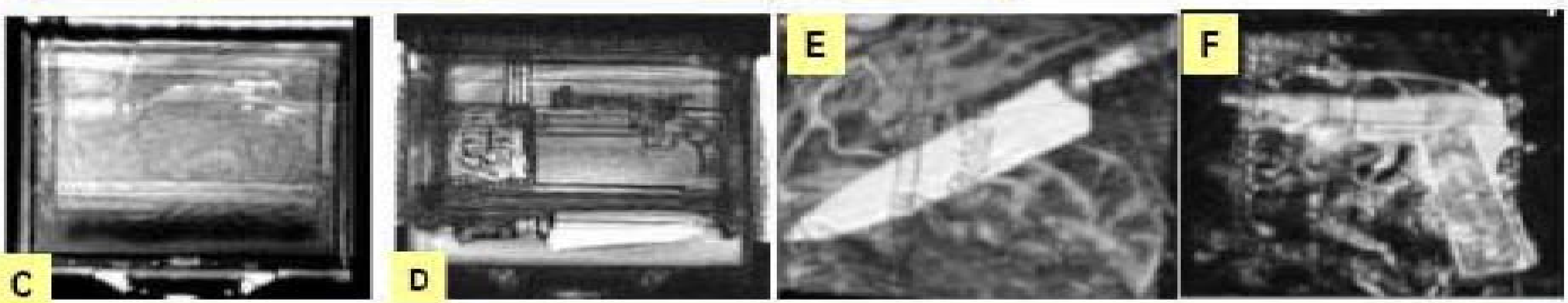
From http://www.scenta.co.uk/_db/_images/terahertz_radiation140.jpg

More Images



From « Large Area THz Imaging and Non-Destructive Evaluation Applications" by David ZIMDARS, Jeffrey S. WHITE, G. STUK, A.CHERNOVSKY, G. FICHTER, S. WILLIAMSON, Picometrix, Michigan, USA

Transmission terahertz images. Left: Attaché Case. Right: Suitcase, approx. 30 in. by 20 in, by 13 in.



Reflection terahertz images. From Left: Return from top of attaché case; return from interior of attaché case showing knife and pistol; knife under jacket; pistol under jacket.

Seeing inside packages

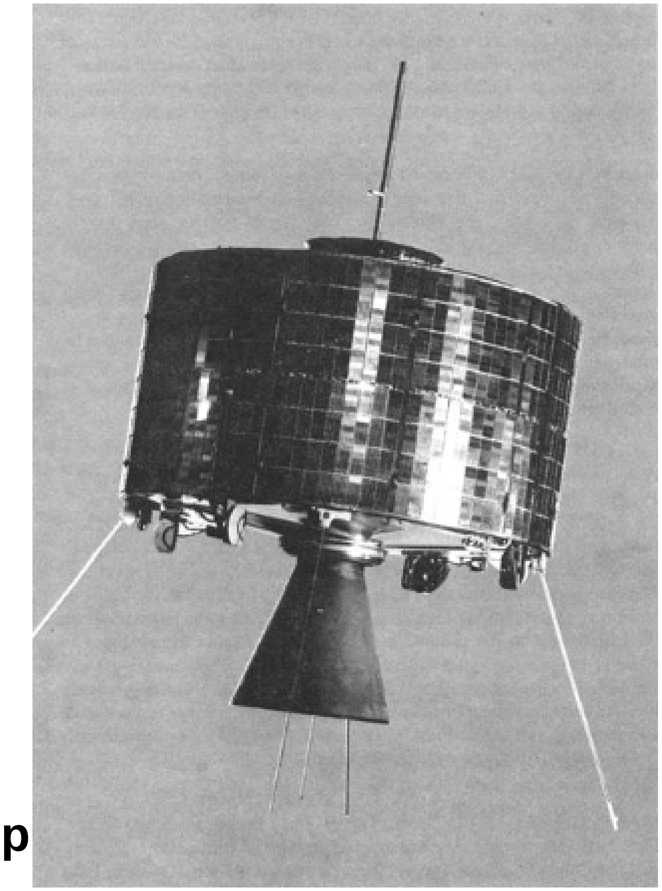
PICOMETRIX
an API company

A THz image of a shipping box filled with packing material contained a plastic knife and a razor blade.

Image from:http://www.advancedphotonix.com/ap_products/thz_app_packageimage.asp

THz wireless covert communications

From: http://www.atl.lmco.com/business/ATL7.php



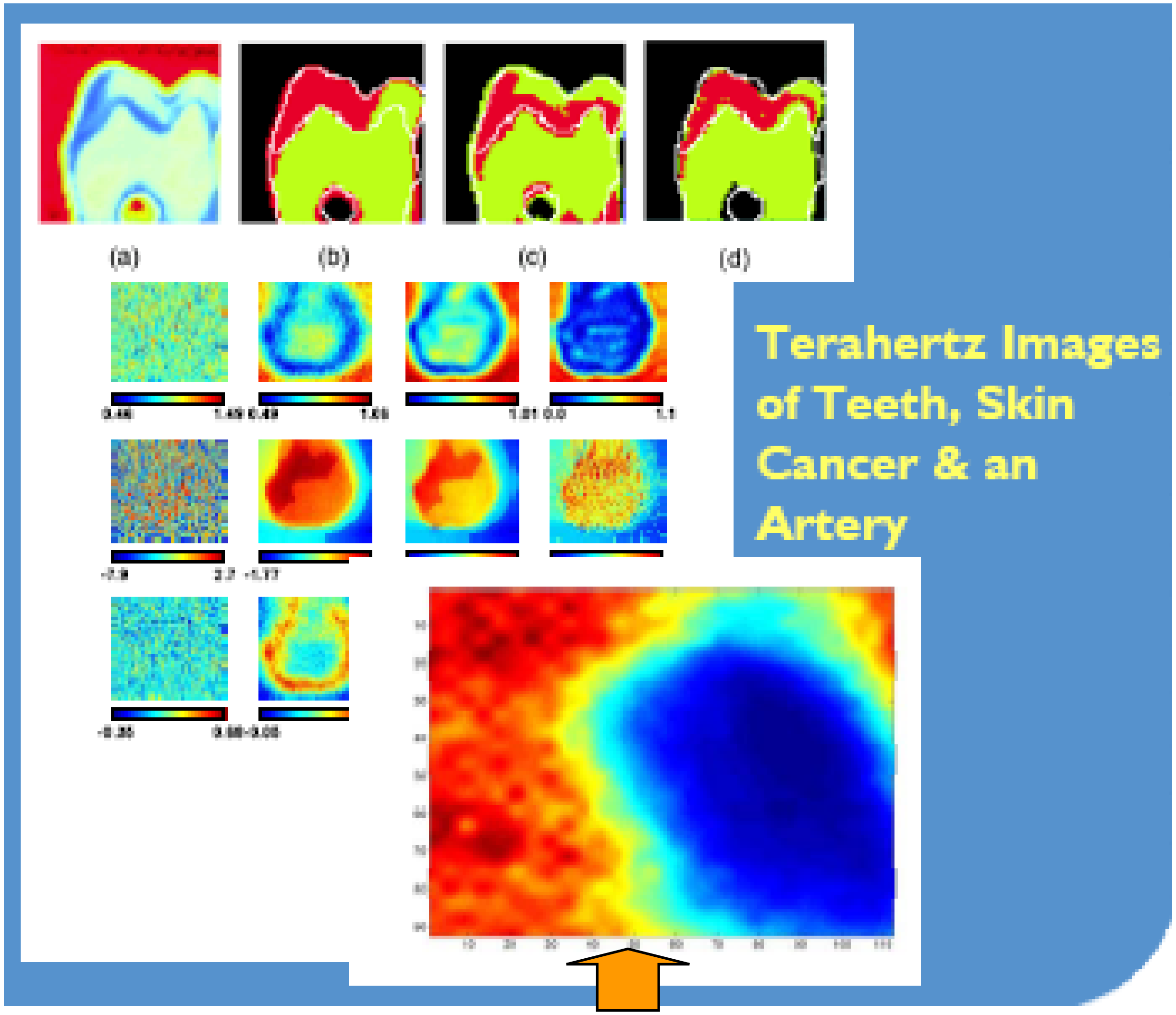
Difficult on Earth (water vapors) – 100's m max?
Possible in space

First generation SYNCOM satellite (NASA image)

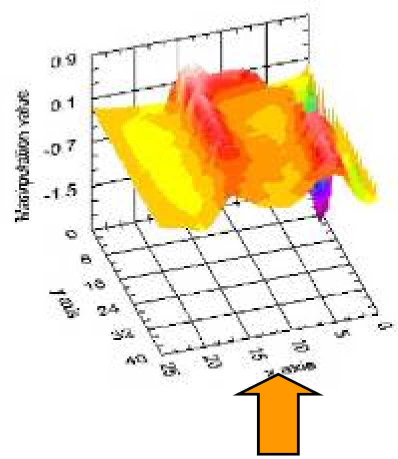
High Resolution Imaging (200 micron resolution)

Image from: http://www.advancedphotonix.com/ap_products/thz_app_hiresimage.asp

THz Applications in Medicine



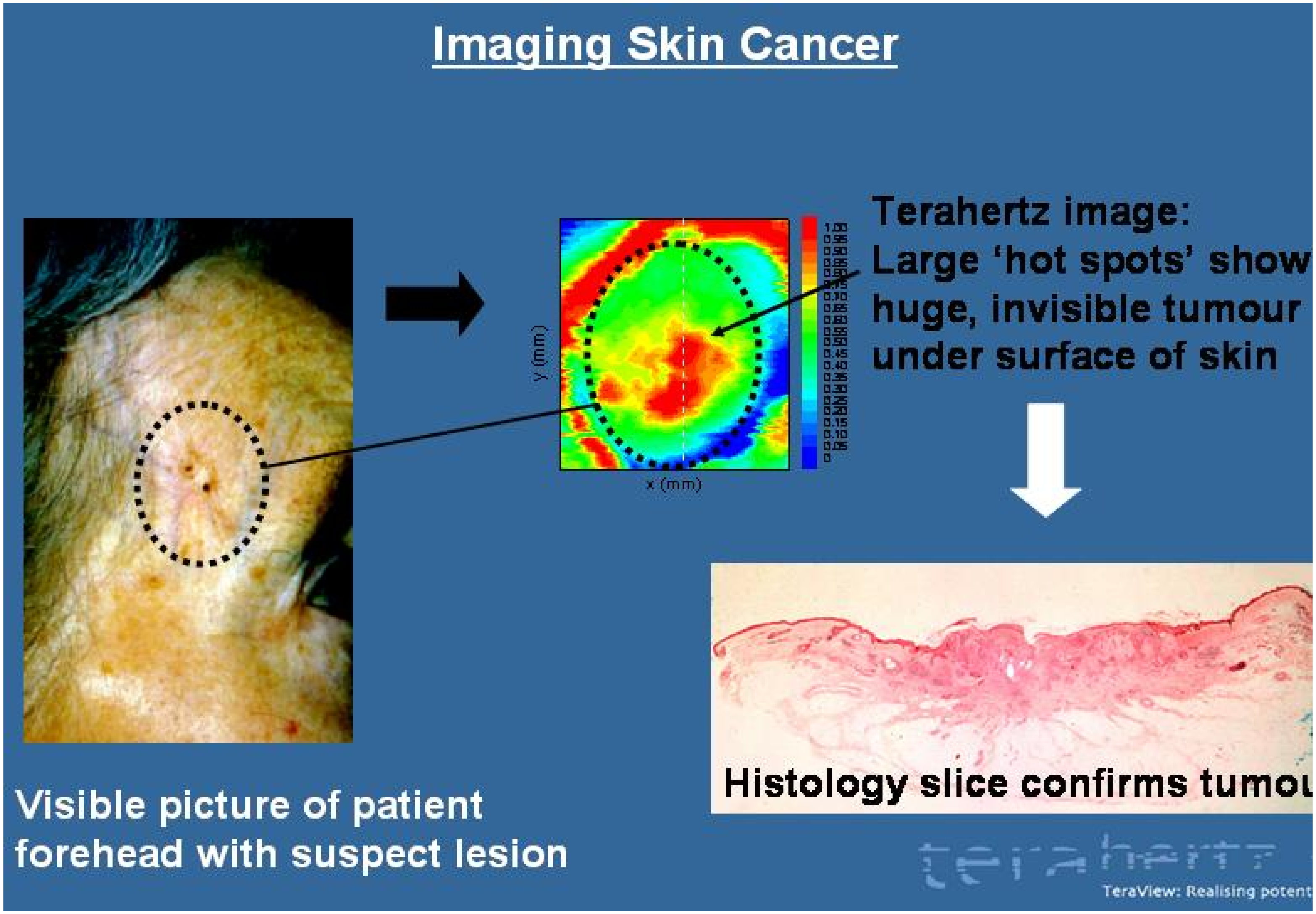
3D Graph of demineralized tooth



From http://www.teraview.co.uk/ab_imageLibrary.asp?page=3#

From http://www.ist-optimist.org/pdf/network/pres_ecoc2002/TERAVISION_ECOC2002.pdf

Medical Applications: Skin Cancer Imaging



http://www.teraview.co.uk/ab_imageLibrary.asp?page=3#

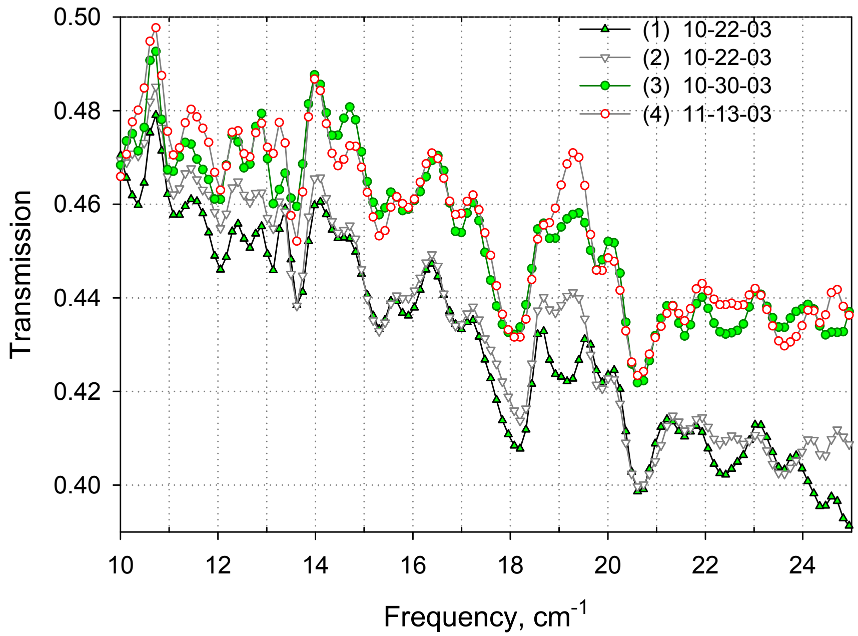
Avoid Multiple Breast Cancer Surgeries by Terahertz Imaging

From www.straightfromthedoc.com/50226711/

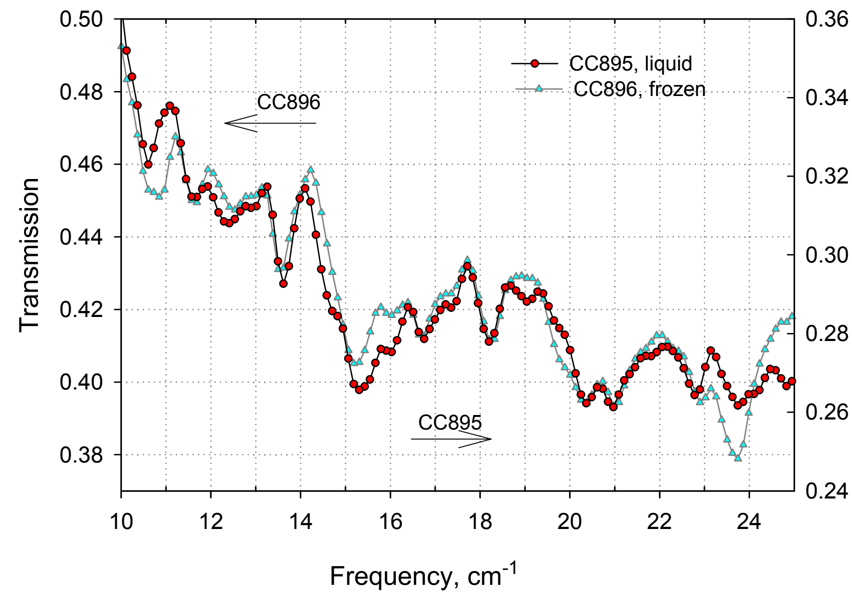
Prostate Cancer

- The most common cancer among men
- 230,000 new cases a year diagnosed
- Autopsy studies of Chinese, German, Israeli, Jamaican, Swedish, and Ugandan men **men** who died of other causes revealed **prostate cancer** in **thirty** **percent of men .**
- But how?
  - PSA – controversial test
  - Biopsy – if positive, you do have cancer
  - If negative – you either do not have it or it has missed your cancer

Prostate Cancer Detection by T-rays



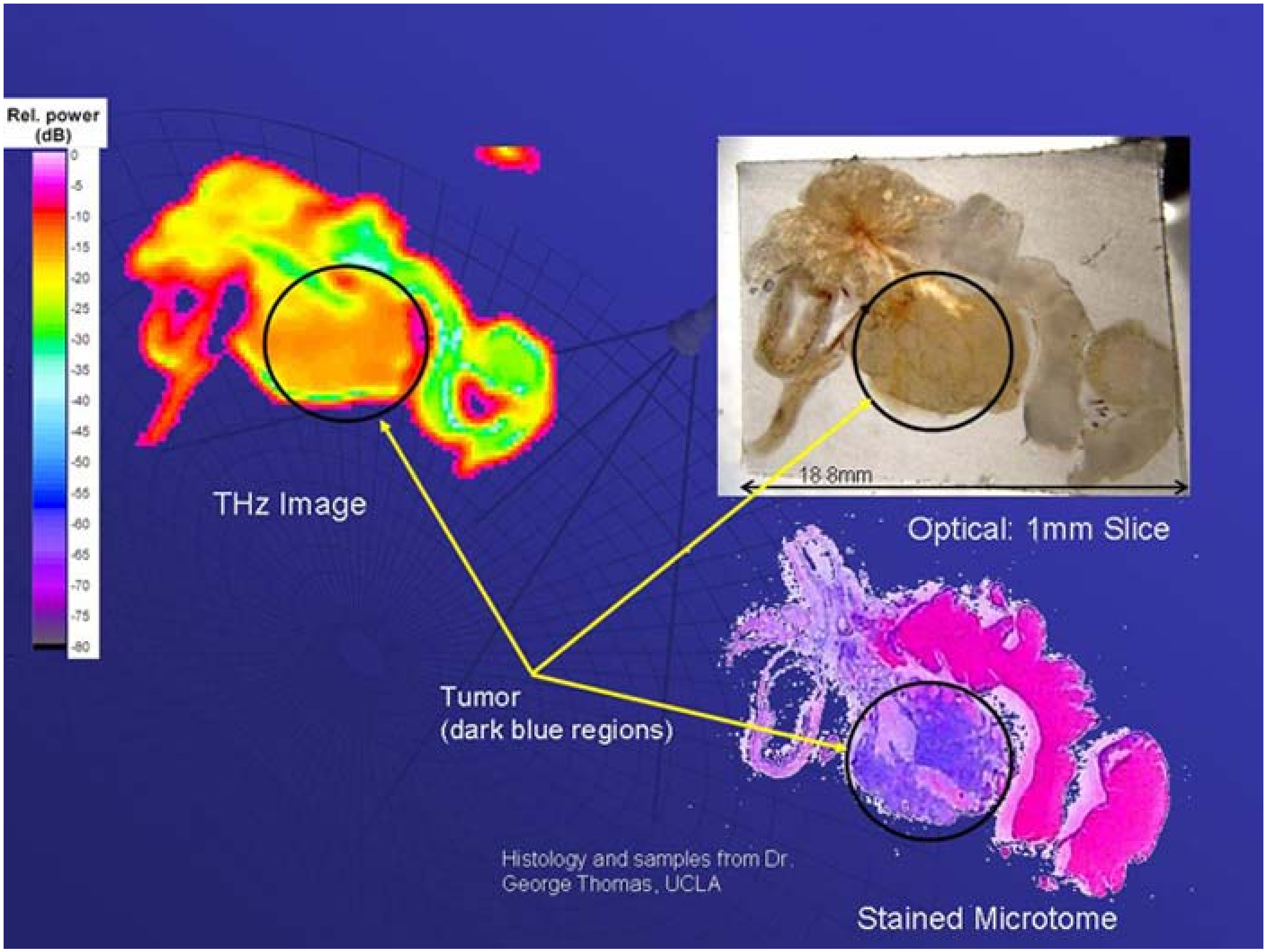
Long term reproducibility of transmission spectra of prostate cancer cells measured after storage of the sample in frozen condition **for several weeks**.



Liquid and frozen samples measured at close orientation have **a similar pattern.**

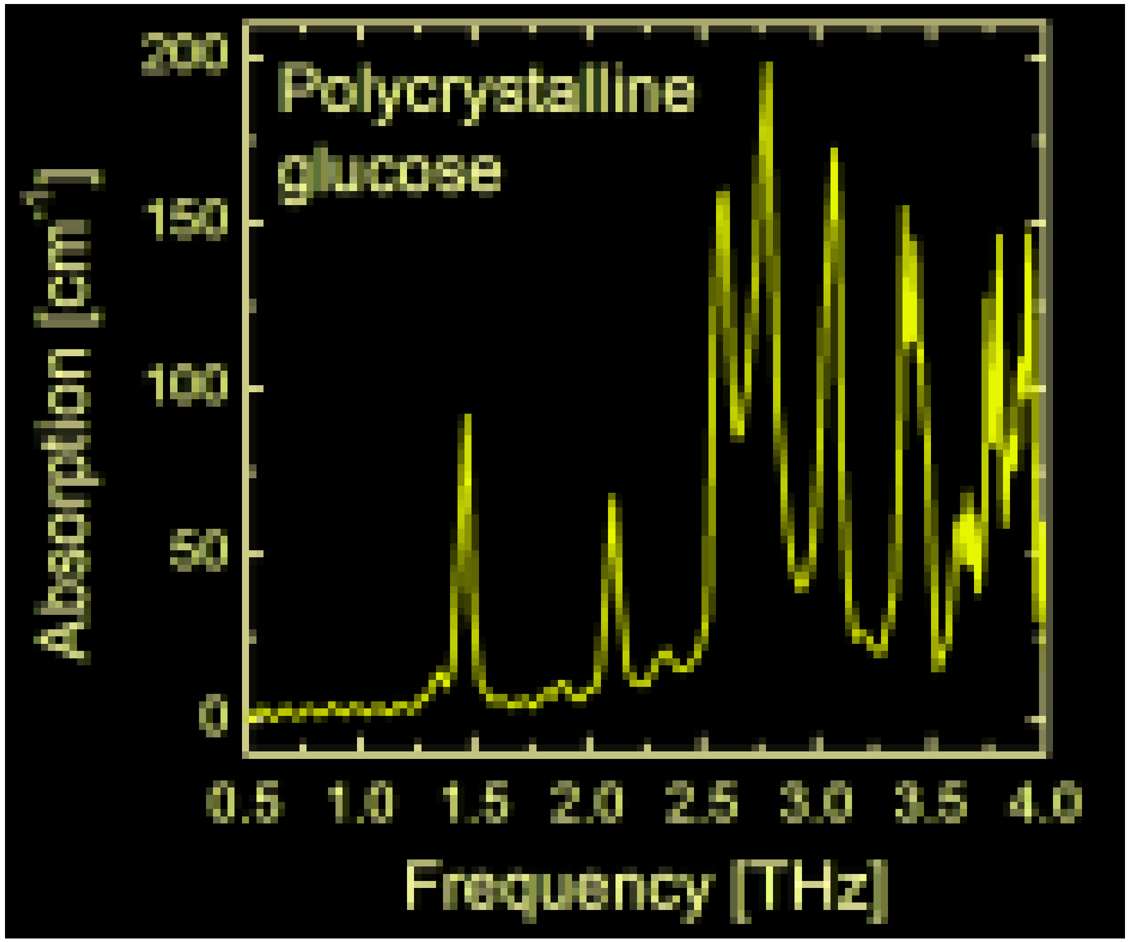
From T. Globus, D. Theodorescu, H. Frierson , T. Kchromova , D. Woolard, “Terahertz spectroscopic characterization of cancer cells”, presented at SPIE Conference “Advanced Biomedical and Clinical Diagnostic Systems III”, San-Jose, January 2005, Proceedings V. 5692-42, and published in *Progress in Biomedical Optics and Imaging*, Vol 6, No7, p 233-240, 2005, by permission

A mouse prostate section with tumor tissue (circle) as imaged with terahertz, optical, and staining techniques



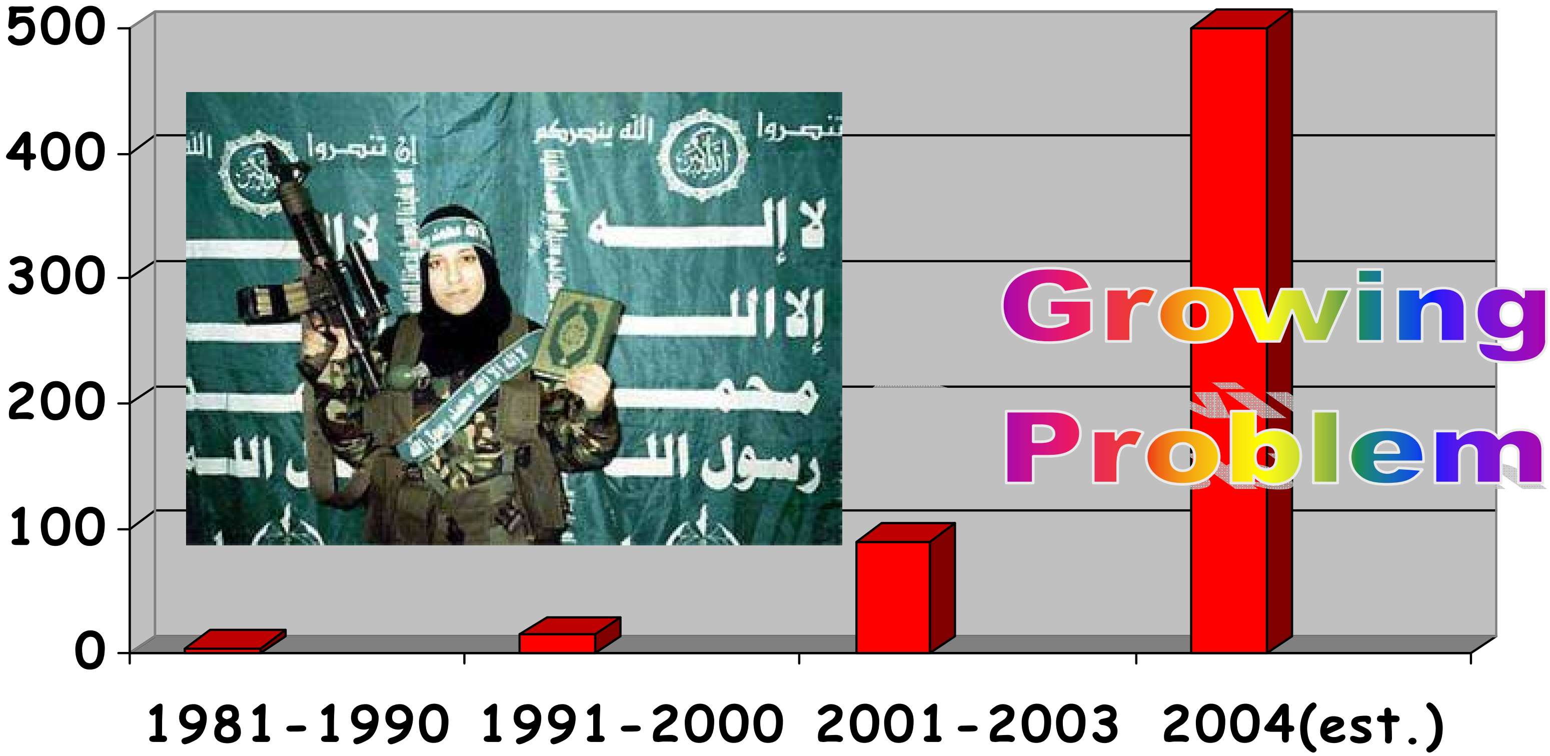
After Peter Siegel, www.nibib.nih.gov/HealthEdu/eAdvances/21June06

THz Spectrum of Sugar



From http://oldwww.com.dtu.dk/research/Nanophotonics/sugarspectrum_small.png

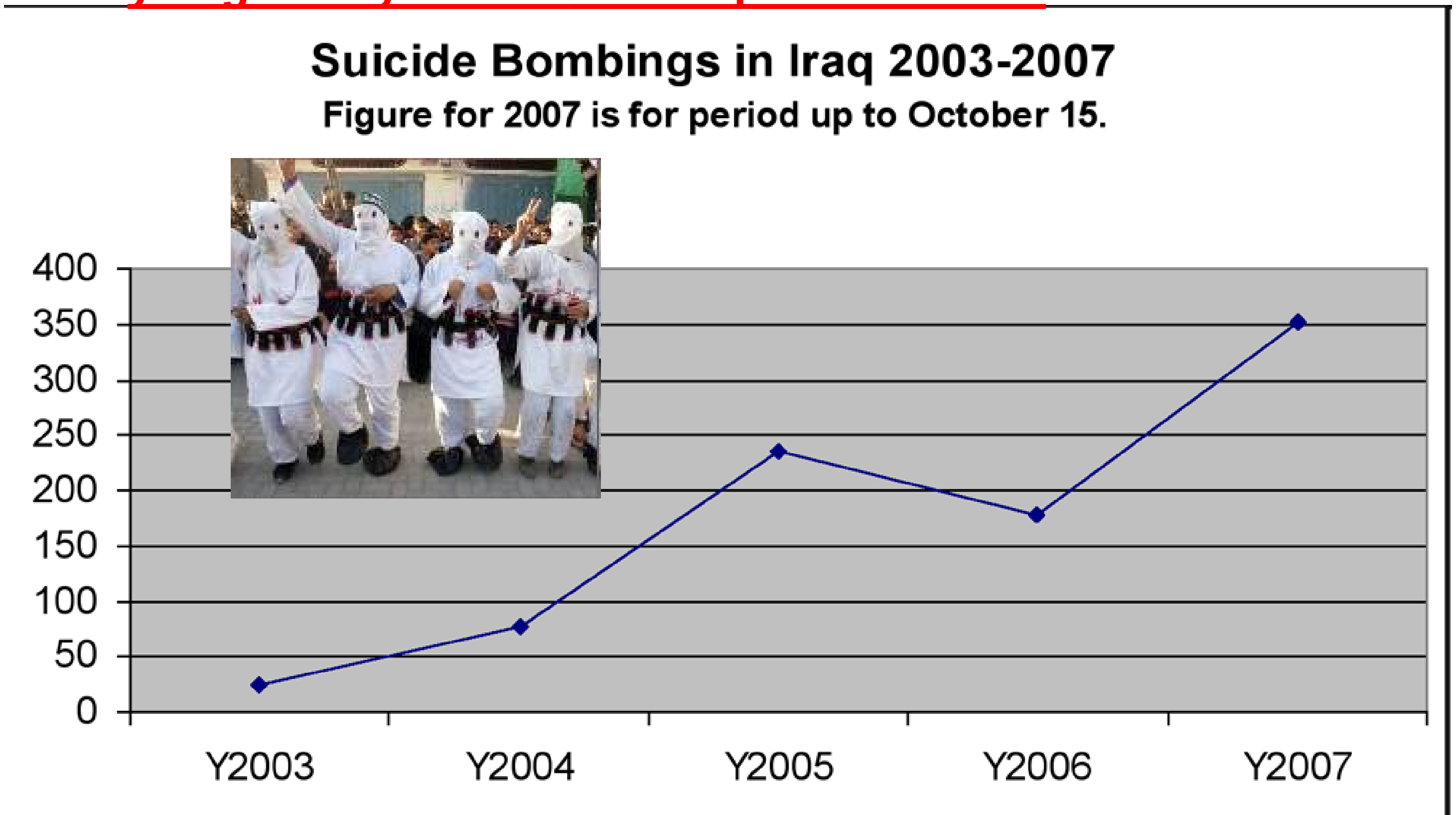
Explosive Detection: Number of Suicide Attacks per Year



From (data for 1981-2003 are from Y. Chen, H. Liu, M. J. Fitch, R. Osiander, J. B. Spicer, M. Shur, X. -C. Zhang, THz Diffuse Reflectance Spectra of Selected Explosive and Related Compounds, SPIE, Florida NATO Science, Society, Security News, No 68, p. 3, provided to NATO by Dr. Scott Atran

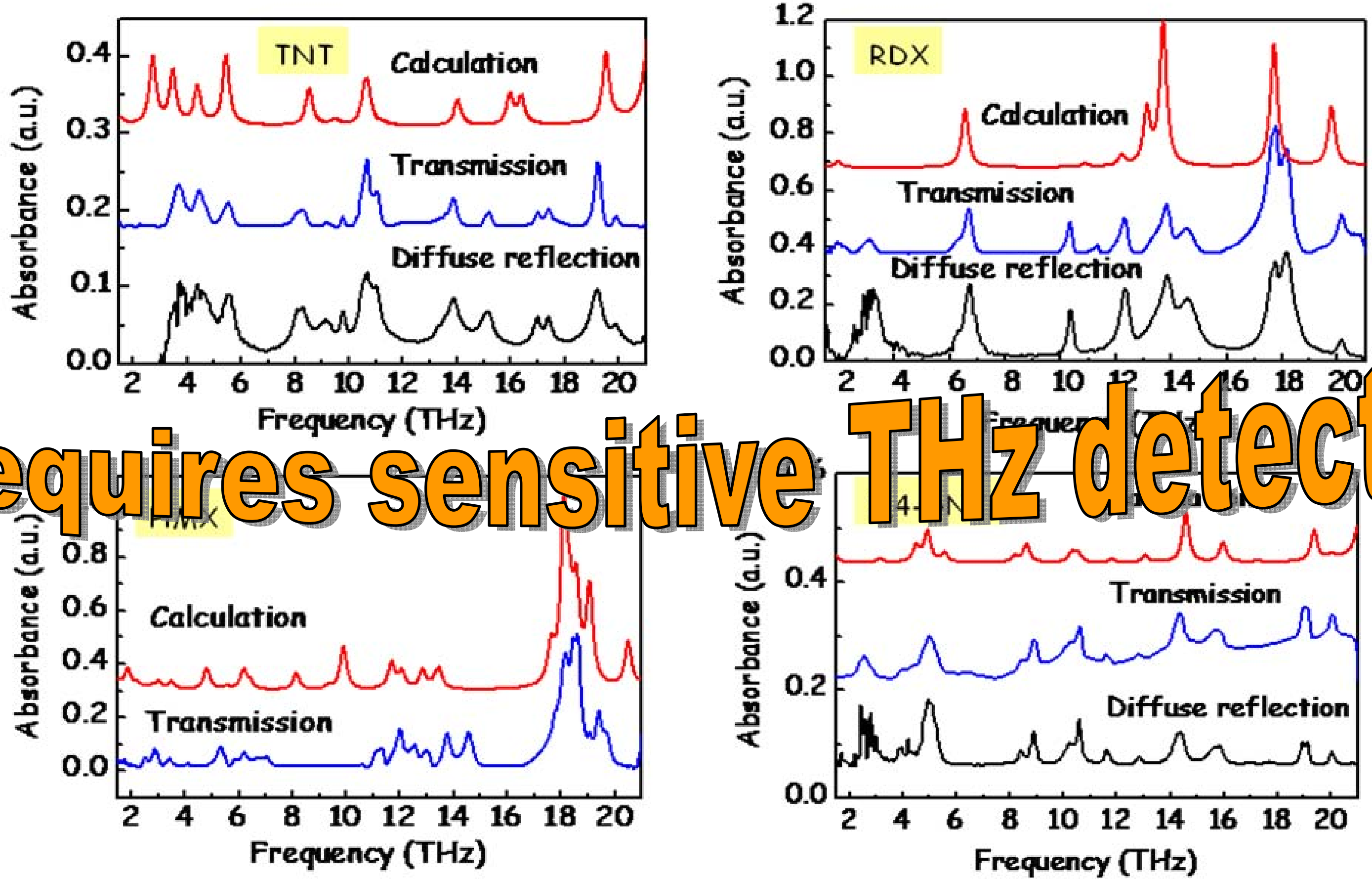
Suicide Bombings in Iraq 2003- October 15 2007

Picture from yaleglobal.yale.edu/article.print?id=3749



From www.motherjones.com/news/feature/2007/11/iraq...

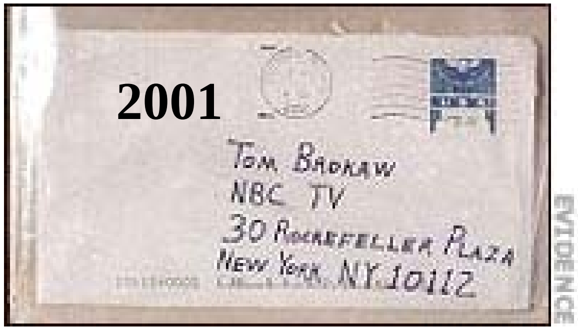
THz Explosive Detection



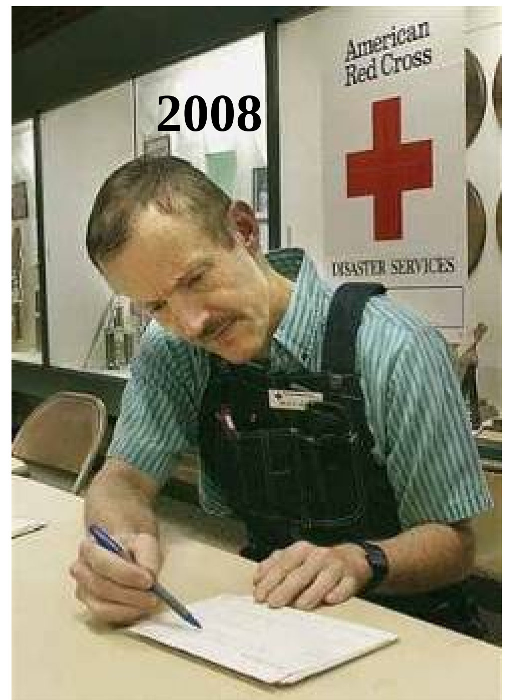
Requires sensitive THz detectors

Y. Chen, H. Liu, Haibo; M. J. Fitch, Rosined, J. B. Spicer, M. S. Shur, X. C. Zhang, THz diffuse reflectance spectra of selected explosives and related compounds, Passive Millimeter-Wave Imaging Technology VIII. Edited by Appleby, Roger; Wikner, David A. Proceedings of the SPIE, Volume 5790, pp. 19-24 (2005)

THz applications – recent reminder



From www.crimelibrary.com/.../anthrax/3.html



Army scientist Bruce E. Ivins

From http://www.wkrg.com/national/article/suicide_latest_twist_in_7_year_anthrax_saga/16504/

Terahertz Detection of Biological Agents

A. G. Markelz, A. Roitberg and E. J. Heilweil

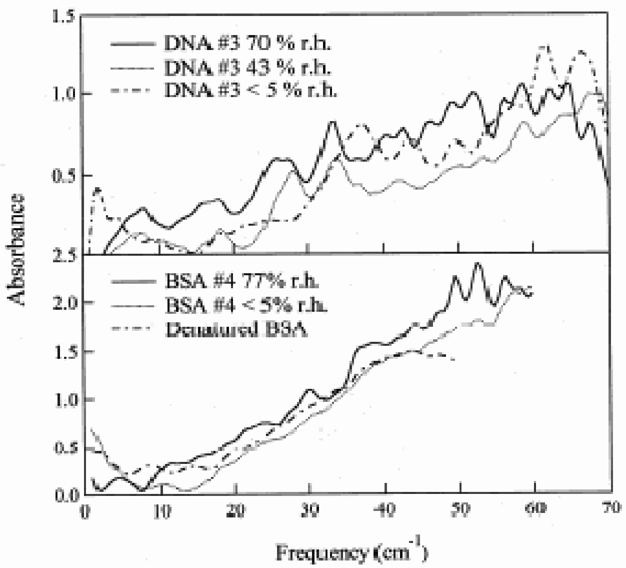


Fig.1 Different DNA samples' absorbance of THz .

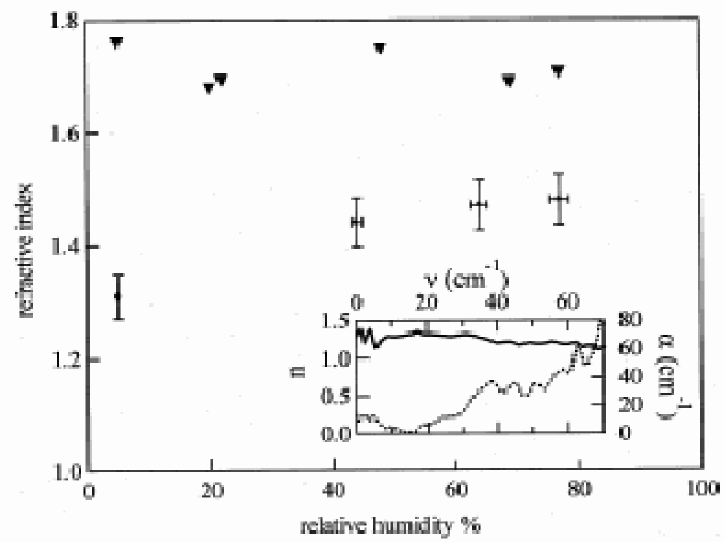


Fig.2 Refractive index of various DNA samples as function of r.h. at ν=25cm^{-1}. Inset: real part and absorption spectra of sample DNA3#.

From http://www.rensselaer.edu/~zhangxc/abouthome.htm

THz active scanners in airports

Adding THz scanning to this airport ion mass spectrometer sensor will reduce the number of false alarms and will test under clothing

From Valerie J. Brown T Rays vs. Terrorists: Widening the Security Spectrum
***Environmental Health Perspectives* Volume 114, Number 9, September 2006**

Tutorial Outline

- History
- Applications
- **Terahertz Photonics**
- Terahertz Electronics
- Plasma wave electronics
- Terahertz properties of grainy multifunctional materials
- Conclusions and future work

Terahertz Photonics

•Sources

–Photo-Dember Effect

–Current Transient (Austin switch – higher power)

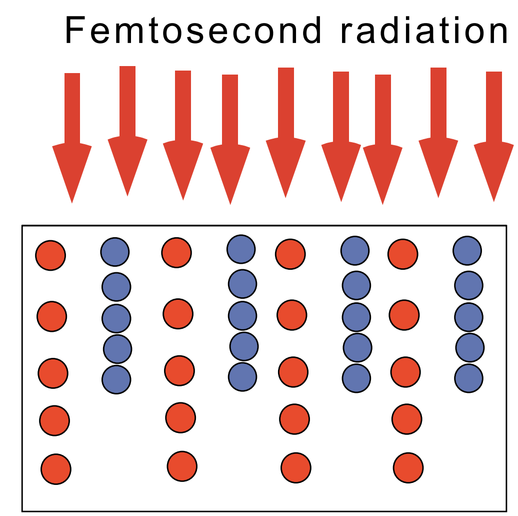
–Optical Rectification (larger band width)

–Quantum Cascade Lasers

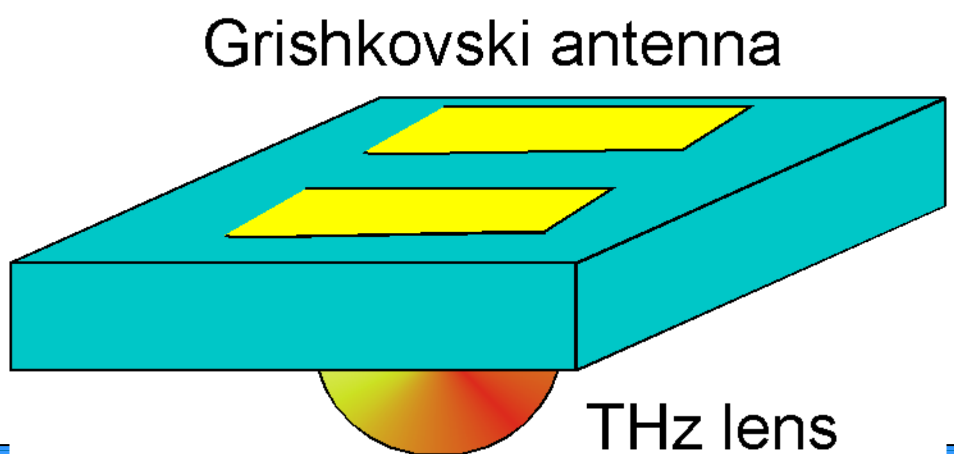
•Detectors

–Current Transient (Austin switch)

Broadband radiation

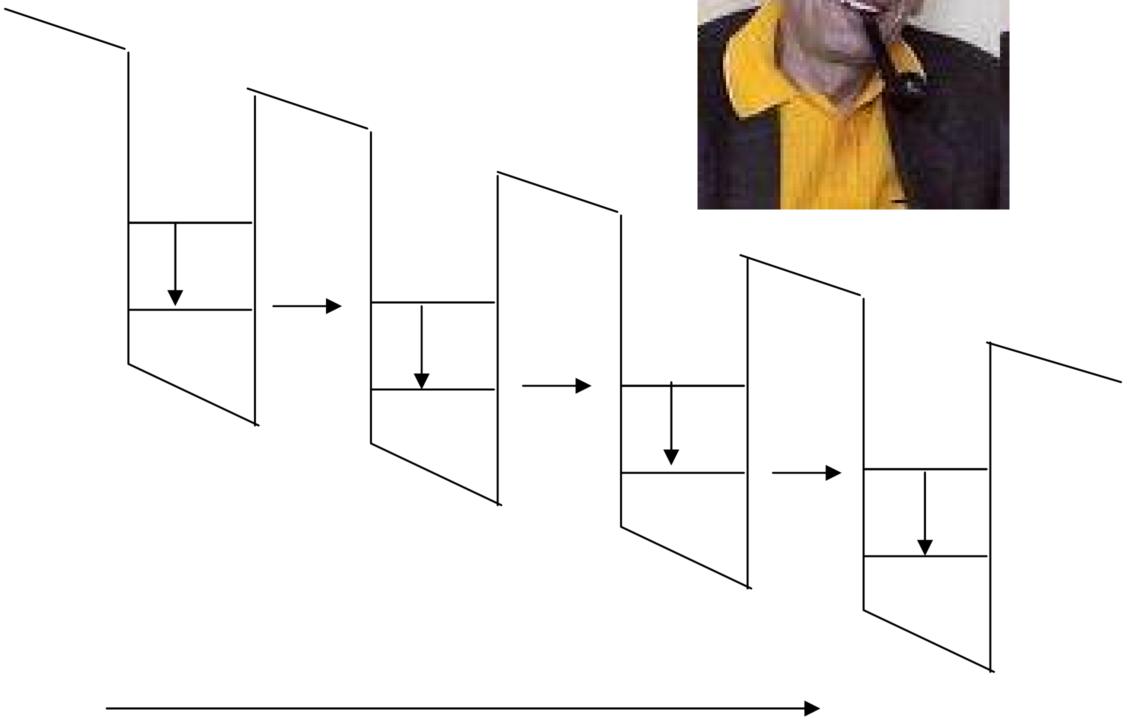


Electrons (red) diffuse deeper into semiconductor, then come back to recombine with holes (blue)



Quantum Cascade Laser

Energy



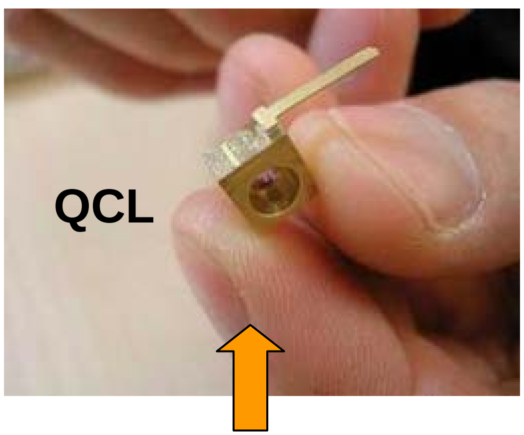
Distance

R. F. Kazarinov and R. A. Suris **Sov. Phys. Semicond. v.5, #4, pp.707-709 (1971)**

THz QCL

B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode," Optics Express, **13**, 3331-3339 (2005)

3 THz at 164 K



From http://images.pennnet.com/articles/lfw/thm/th_0607lfwn2.jpg

Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode

Benjamin S. Williams, Sushil Kumar, and Qing Hu

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

qhu@mit.edu

John L. Reno

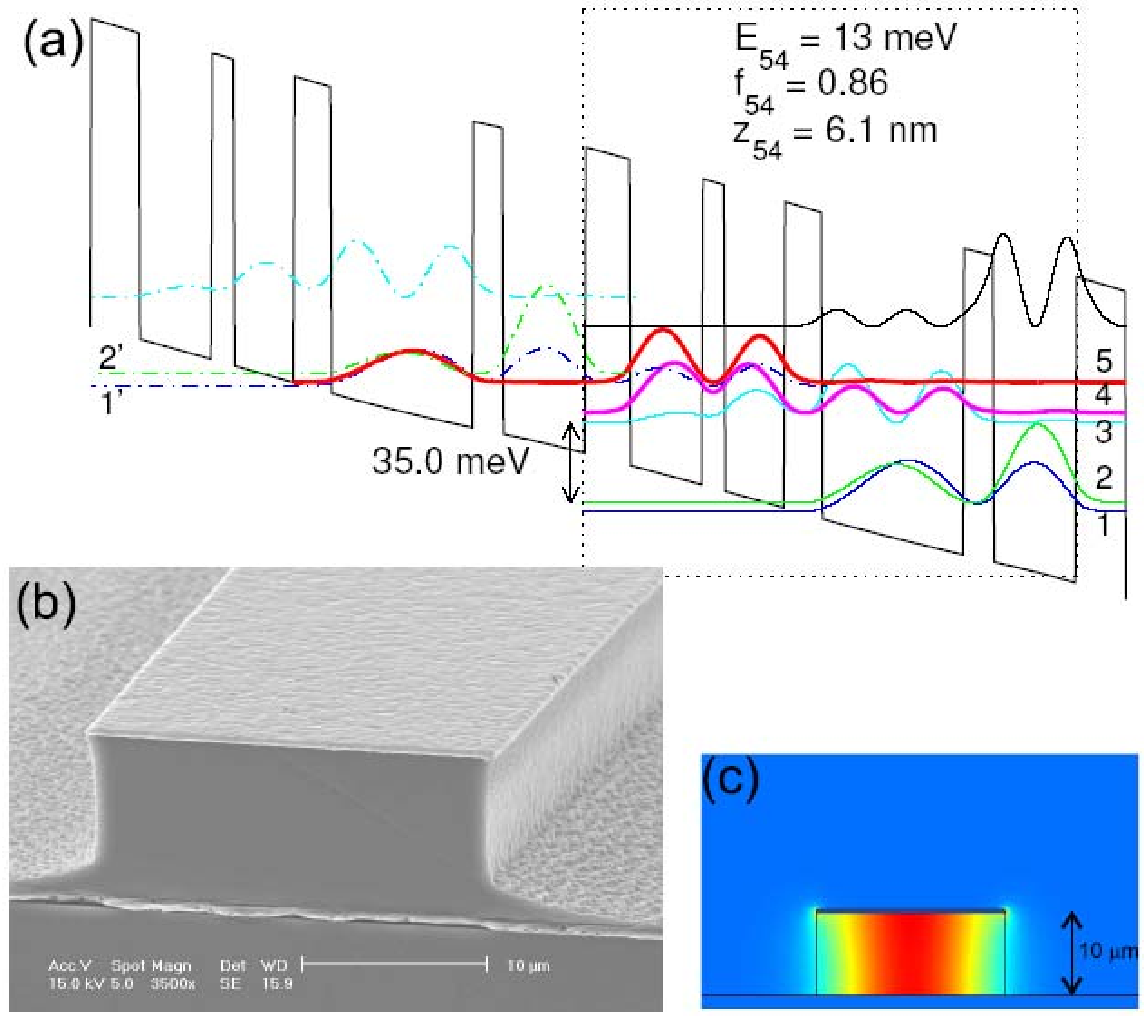
Sandia National Laboratories, Dept 1123, MS 0601, Albuquerque, New Mexico 87185-0601

Abstract: We report the demonstration of a terahertz quantum-cascade laser that operates up to 164 K in pulsed mode and 117 K in continuous-wave mode at approximately 3.0 THz. The active region was based on a resonant-phonon depopulation scheme and a metal-metal waveguide was used for modal confinement. Copper to copper thermocompression wafer bonding was used to fabricate the waveguide, which displayed improved thermal properties compared to a previous indium-gold bonding method.

OCIS codes: (140.3070) Infrared and far-infrared lasers, (140.5960) Semiconductor lasers, (230.5590) Quantum-well devices.

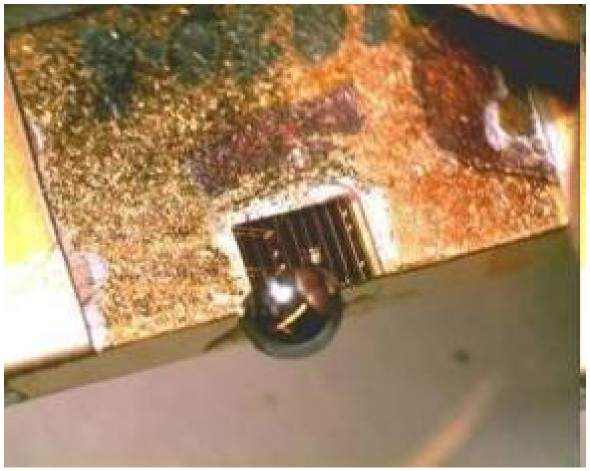
Quantum Cascade Laser

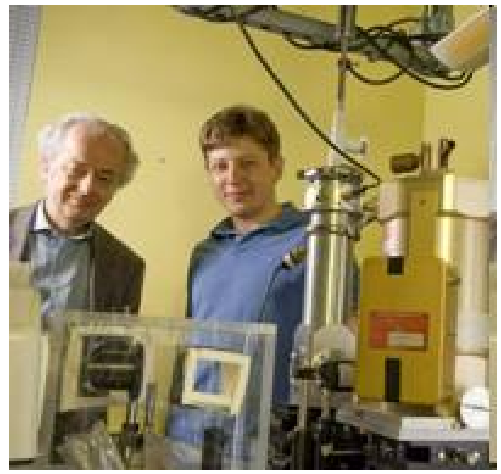
From B. S. Williams, S. Kumar, Q. Hu, and J. L. Reno, "Operation of terahertz quantum-cascade lasers at 164 K in pulsed mode and at 117 K in continuous-wave mode," Optics Express, **13**, 3331-3339 (2005)



Room Temperature THz laser

Mikhail Belkin and Federico Capasso



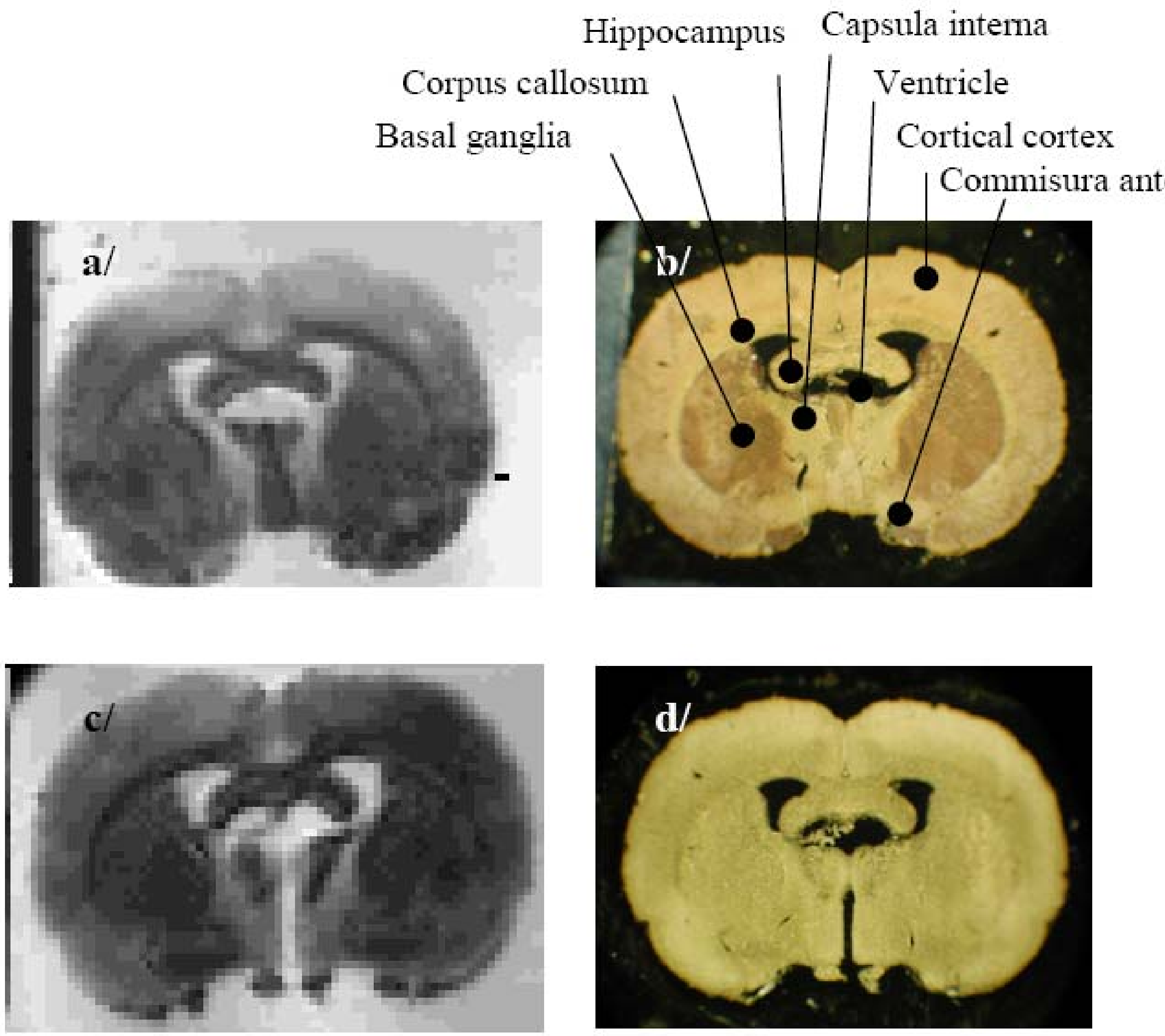


APL, May 19, 2008

A photograph of a bar with 10 terahertz laser sources developed by the Harvard University engineers. One of the lasers is connected to the contact pad (seen on the left) by two thin gold wires. A 2mm-diameter Silicon hyper-hemispherical lens is attached to the facet of the device to collimate the terahertz output. The emission frequency is 5 THz, corresponding to a wavelength of 60 microns. (Credit: Courtesy of the Capasso Lab, Harvard School of Engineering and Applied Sciences)

Harvard University (2008, May 20). First Room-temperature Semiconductor Source Of Coherent Terahertz Radiation Demonstrated. *ScienceDaily*. Retrieved August 29, 2008, from http://www.sciencedaily.com- /releases/2008/05/080519083023.htm

THz Imaging with Quantum Cascade Laser



From J. Darmo, V. Tamosiunas, G. Fasching, J. Kroll, K. Underainer, M. Beck, M. Giovannini, and J. Faist, Optics Express, vol. 12, No. 9, p.1879 (2004)
Courtesy of Professor Underainer

Optical Rectification

$$P = \alpha E + \beta E^2 + \gamma E^3 + .$$

$$P_x = \alpha E_{xo} \cos(\omega t) + \beta E_{xo}^2 \cos^2(\omega t)$$

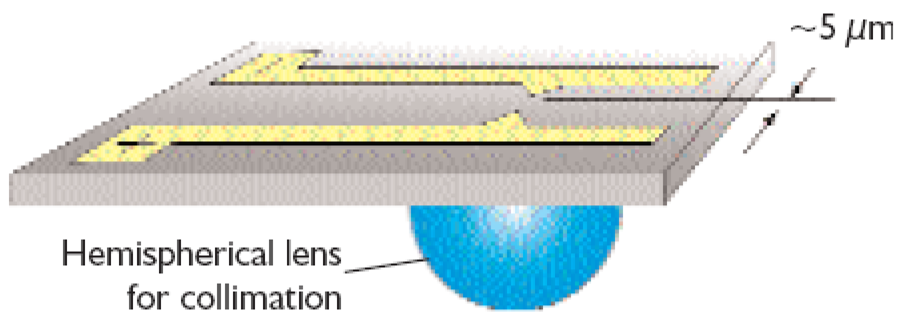
$$\cos^2(\omega t) = \frac{1 + \cos(2\omega t)}{2}$$

DC (i.e. low frequency) component contains
THz frequencies due to
the fs laser pulse waveform

Photoconducting Current (Austin Switch)

$$E_{THz} = \frac{\partial j}{\partial t}$$

$$P_{THz} = \Delta N^2 \frac{1}{6\pi\varepsilon_o} \frac{q^2 a^2}{c^3}$$



ΔN number of electrons

q electronic charge

c speed of light

a acceleration

ε_o vacuum dielectric permittivity

Grischkowsky antenna

Why Si Lens?

THz (0.2 - 2 THz) index of refraction and power absorption

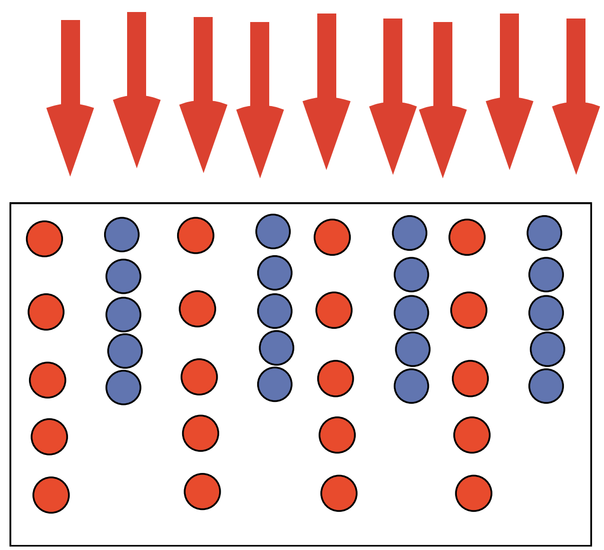
Material	Index of Refraction	Power Absorption (cm^{-1})
Fused silica	1.952	1.5
Sapphire	n_o =3.070; n_e=3.415	1
Intrinsic Ge	4.002	0.5
High-res GaAs	3.595	0.5
Quartz	n_o =2.108; n_e=2.156	0.1
High-res Si	3.418	0.05

Data from: D. Grischkowsky, S. Keiding, M. van Exter and C. Fattinger, *Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors, Journal of the Optical Society of America B: Optical Physics* **7**(10) (1990) 2006–2015.

Photo-Dember Effect

Effective in narrow band-gap
with large electron mobility and low hole mobility (InSb, InN).

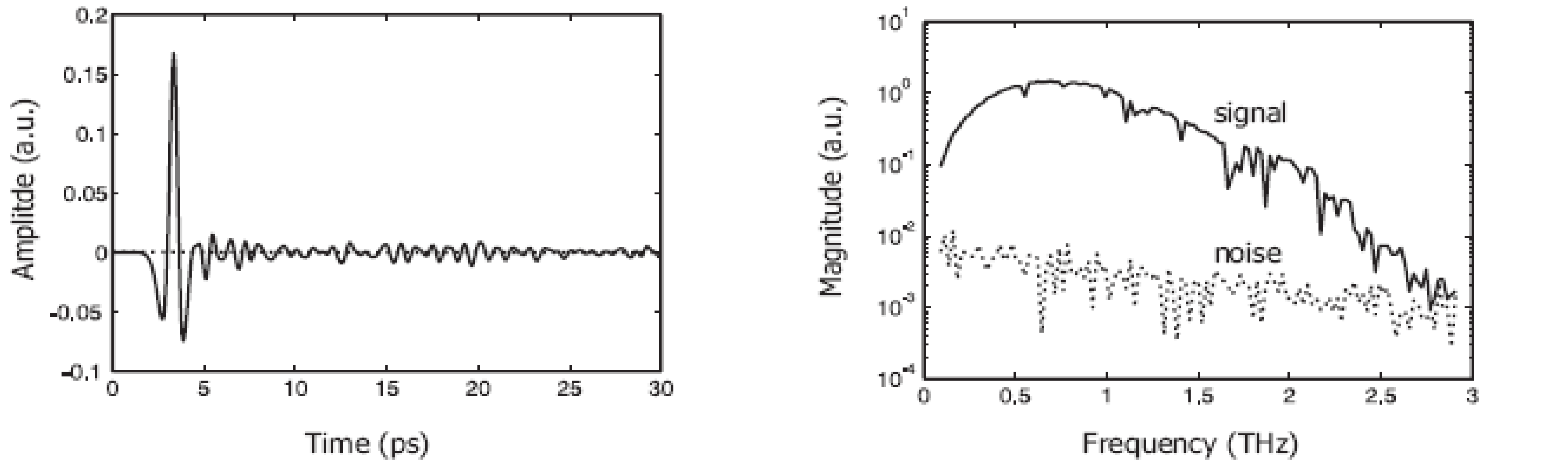
Femtosecond radiation



Electrons (red) diffuse
deeper into semiconductor,
then come back to recombine
with holes (blue)

THz Pulse in Time and Frequency Domain

Mickan & Zhang



(a) Time-domain T-ray electric field pulse

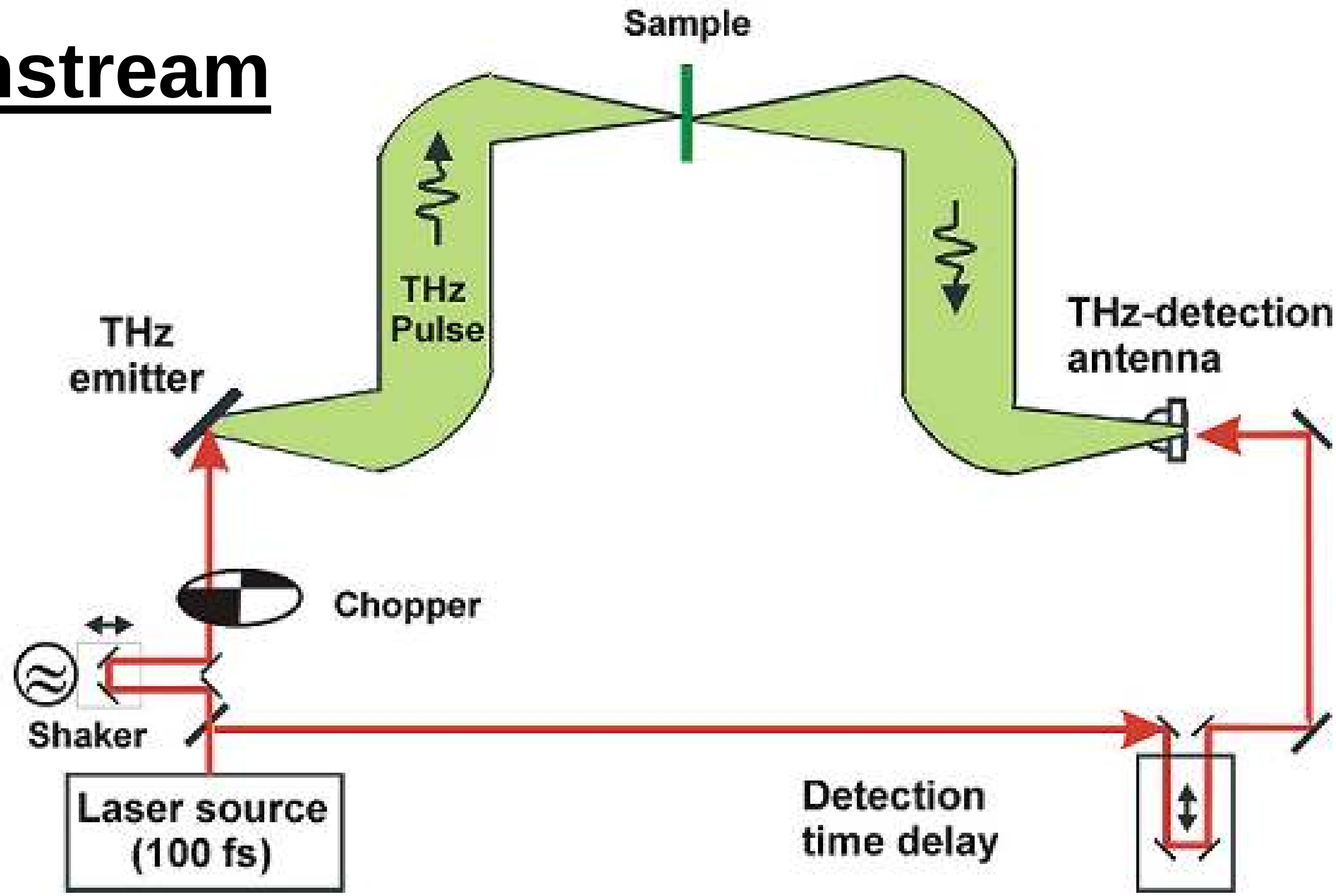
(b) Spectral components of the T-ray pulse

Fig 2. The electric field of a typical broadband T-ray pulse, showing the ps duration and THz bandwidth. This pulse was generated from surface currents in unbiased GaAs, generated by 100-fs laser pulses with a pulse repetition frequency of 82 MHz. The T-rays propagated though 50 cm of air, and were detected by electro-optic sampling in ZnTe. The spectrometer was at room temperature and humidity; the oscillations in the tail of the time-domain pulse, and the frequency dips visible in the spectrum at 0.56, 0.75 and 1.1 THz are due to absorption of water molecules in the air.[6] The noise level depends on averaging time in the lock-in amplifier; these measurements were averaged with a 100-ms time constant.

Courtesy of Professor X. C. Zhang, RPI

THz Photonics: Time Domain THz Spectroscopy

Mainstream



From www.brucherseifer.com/html/projects.html

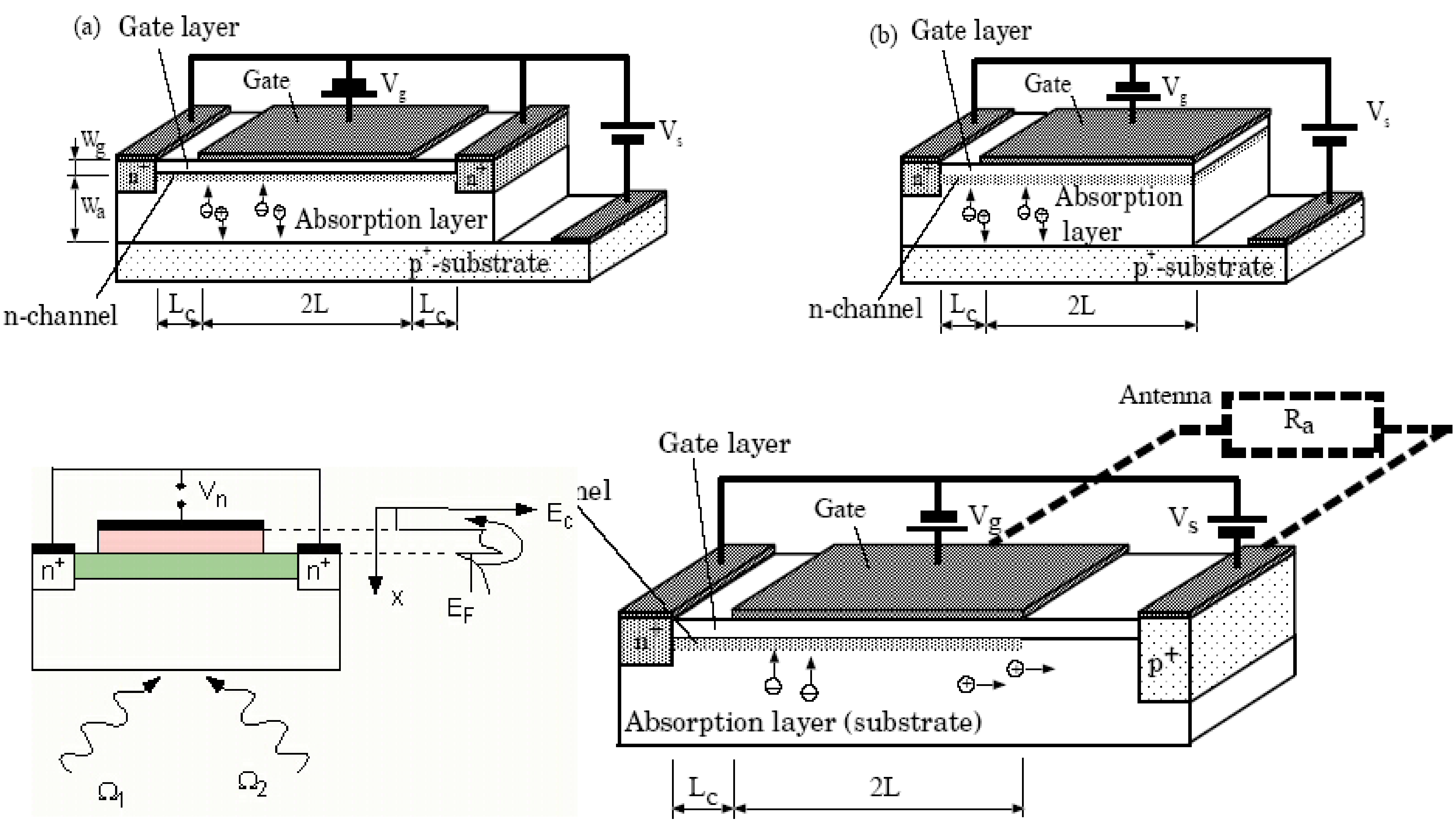
Photomixing

- Modulated infrared radiation can cause the resonant excitation of plasma oscillations in quantum well diode and transistor structures
- This effect provides a new mechanism for the generation of tunable terahertz radiation
- We developed a device model for a quantum well photomixer*
- The proposed device can significantly surpass standard quantum well infrared photodetectors. *

==============================

* After V. Ryzhii, I. Khmyrova, and M. S. Shur, Terahertz photomixing in quantum well structures using resonant excitation of plasma oscillations, J. Appl. Phys. Vol. 91, pp. 1875 (2002)

Resonant Photomixer



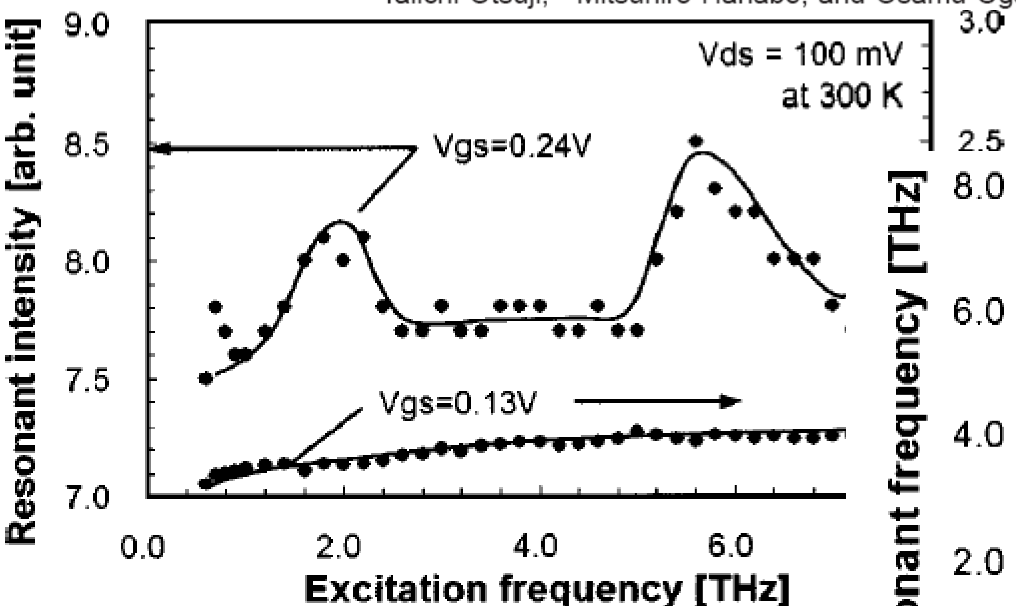
V. Ryzhii, A. Satou, I. Khmyrova, M. Ryzhii, T. Otsuji, and M. Shur, "Analytical and computer models of terahertz HEMT-photomixer," SPIE, Conference on Microwave and Terahertz Photonics, Vol. 5466, pp. 210-217, Strasbourg, April 2004

Experimental Observation of Resonant Photomixing

APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 11 13 SEPTEMBER 2004

Terahertz plasma wave resonance of two-dimensional electrons in InGaP/InGaAs/GaAs high-electron-mobility transistors **p. 2119**

Taiichi Otsuji,[a)] Mitsuhiro Hanabe, and Osamu Ogawara



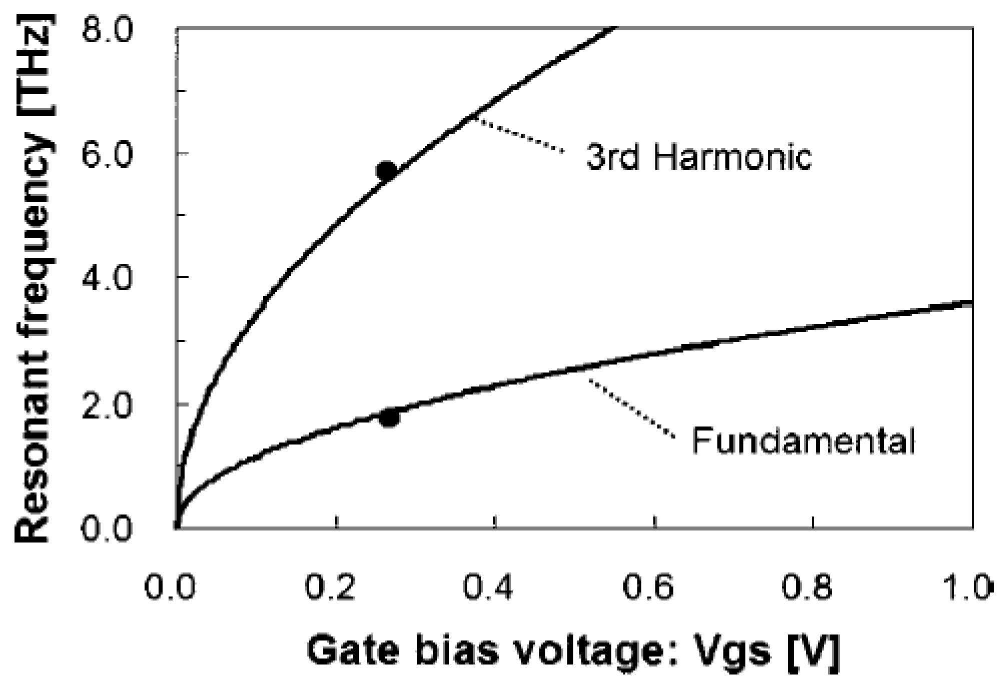


FIG. 3. Measured plasma resonant intensity vs the e
drain node is biased at 100 mV to the source (g
$V_{gs}=0.24$ V ($n_s>10^{12}$ cm^{-2}), $\delta_{pm}=30\%$, lower
($n_s<10^{11}$ cm^{-2}), $\delta_{pm}=40\%$.

THz systems (a) TeraView's TPI imaga 2000: 3D THz imaging system for tablet coatings and cores (b) Picometrix

(a)

(b)

From http://www.pharmaceutical-technology.com/contractor_images/teraview/1s-terraview.jpg

From http://www.advancedphotonix.com/ap_products/terahertz.asp

Compact THz Photonics System –Mini-Z

2007 $30,000 Lemelson-Rensselaer Student Prize.

Brian Schulkin (RPI, graduate student of Professor Zhang) has invented an ultralight, handheld terahertz spectrometer

Some of the THz Companies

Coherent, Inc	Fs lasers, optically pumped THz lasers www.CoherentInc.com
Picometrics	THz imaging (THz photonics) www.picometrics.com
Teraview LTD	THz imaging (THz photonics) www.teraview.co.uk
Virginia Diodes, Inc.	Schottky diode multipliers www.virginiadiodes.com

Free Electron laser

$$E_{THz} = \frac{\partial j}{\partial t}$$

$$P_{THz} = \Delta N^2 \frac{1}{6\pi\varepsilon_o} \frac{q^2 a^2}{c^3} \gamma^4$$

γ ratio of mass to rest mass (20)

ΔN number of electrons

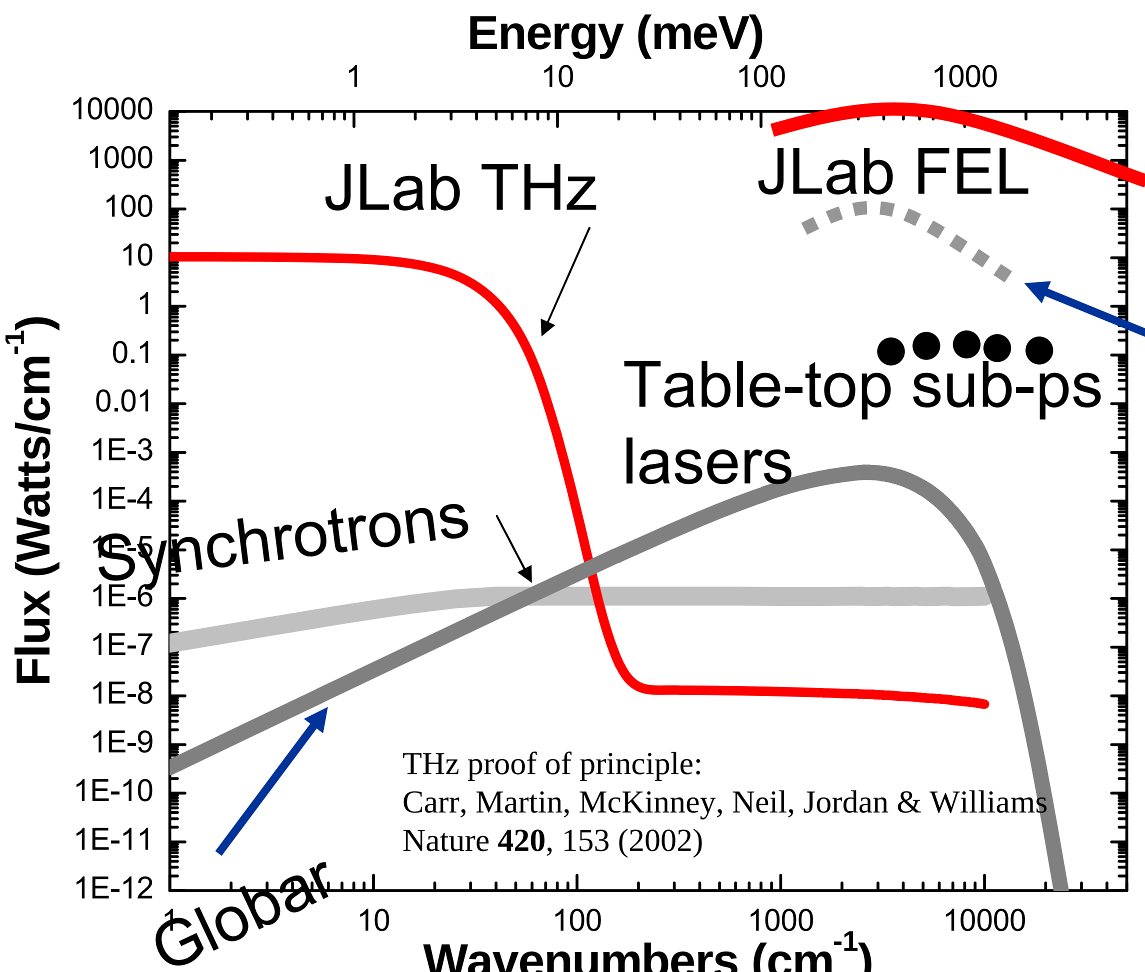
q electronic charge

c speed of light

a acceleration

ε_o vacuum dielectric permittivity

Jefferson Lab facility spectroscopic range



FEL proof of principle: Neil et al. Phys. Rev.Letts **84**, 662 (2000)

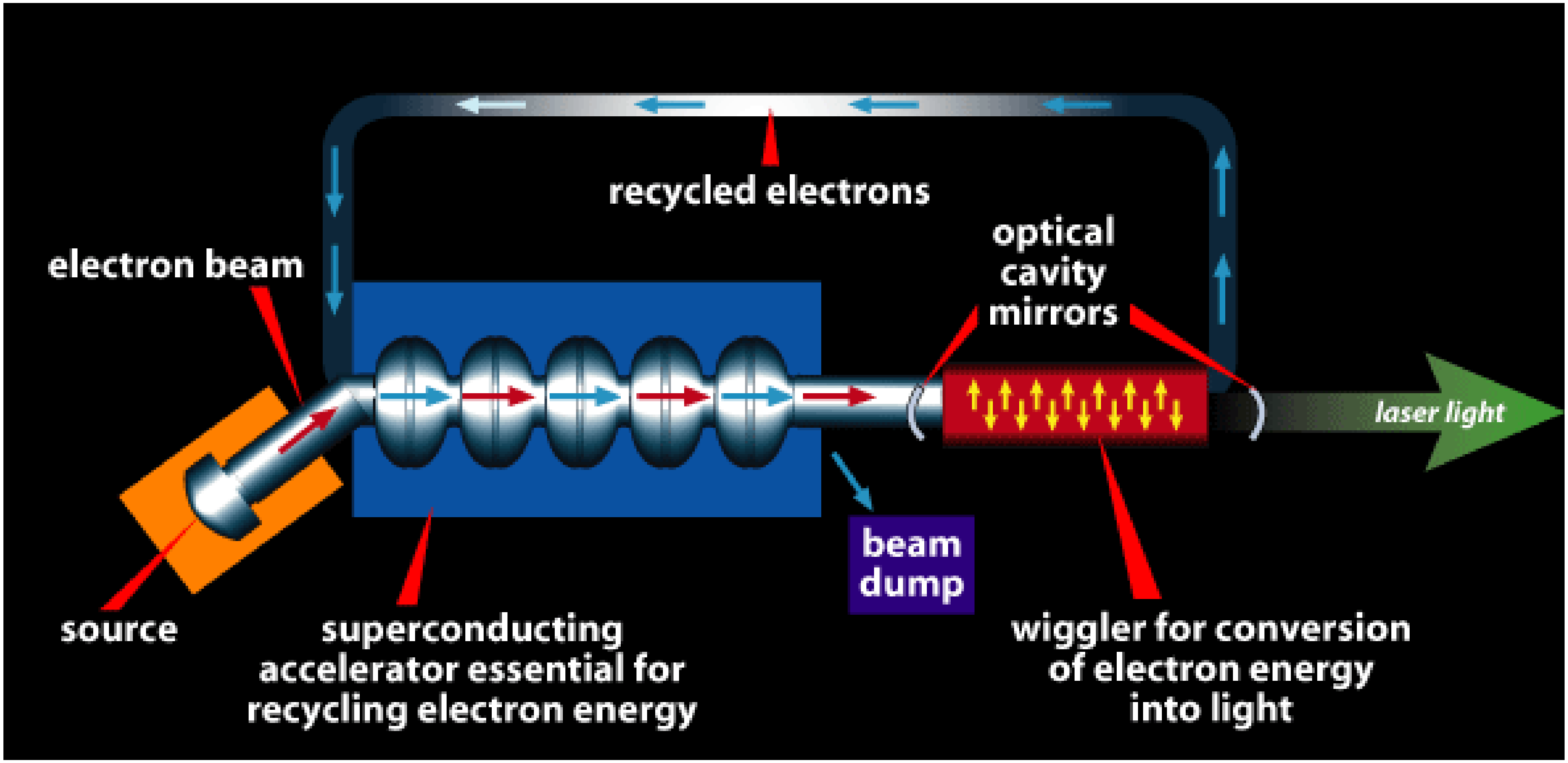
Courtesy of **G.P. Williams Jefferson Lab**

Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Thomas Jefferson National Accelerator Facility

Office of Science
U.S. DEPARTMENT OF ENERGY

Free electron laser



From http://www.jlab.org/FEL/images/FELdiagram.gif

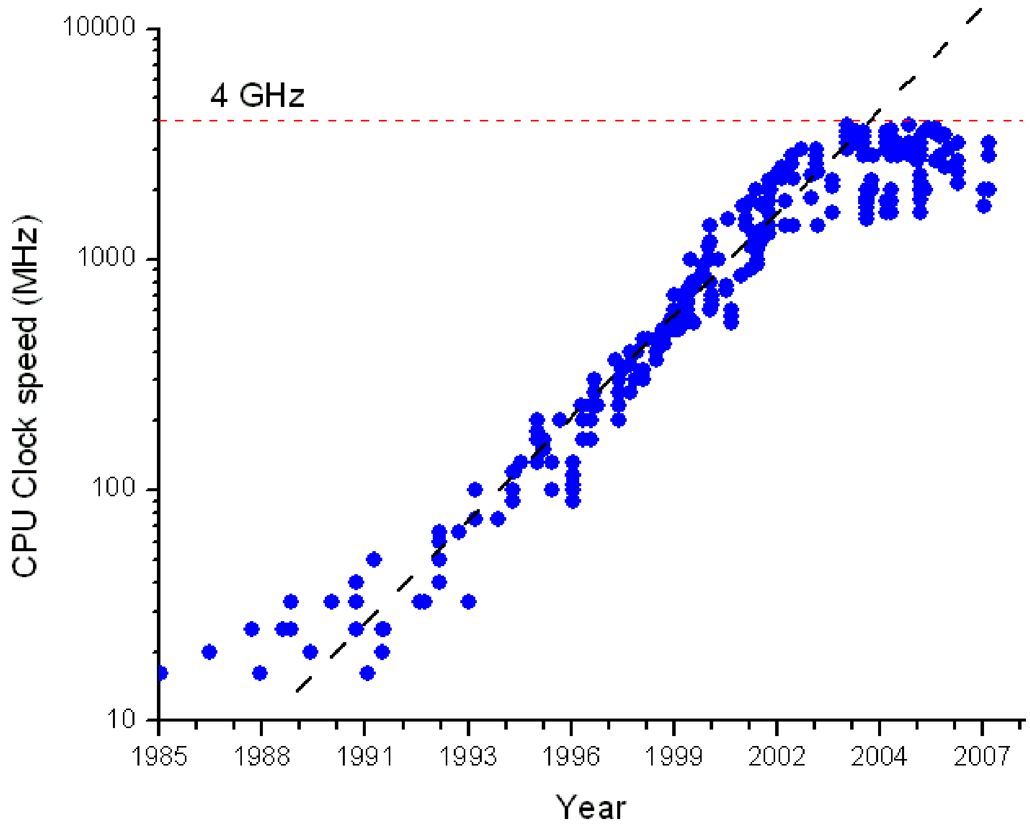
Jefferson Lab Free Electron Lasers

- Wavelength range (IR)1-14μm
- Power/pulse 20 μJ Pulse
- Repetition frequency up to 75 MHz
- Pulse length 500-1700 fs
- Maximum average power>10 kW
- Wavelength range (UV/VIS)250-1000 nm
- Power/pulse 20 μJ
- Pulse repetition frequency up to 75 MHz
- Pulse length300-1700 fs
- Maximum average power>1 kW

From: http://www.jlab.org/FEL/terahertz/

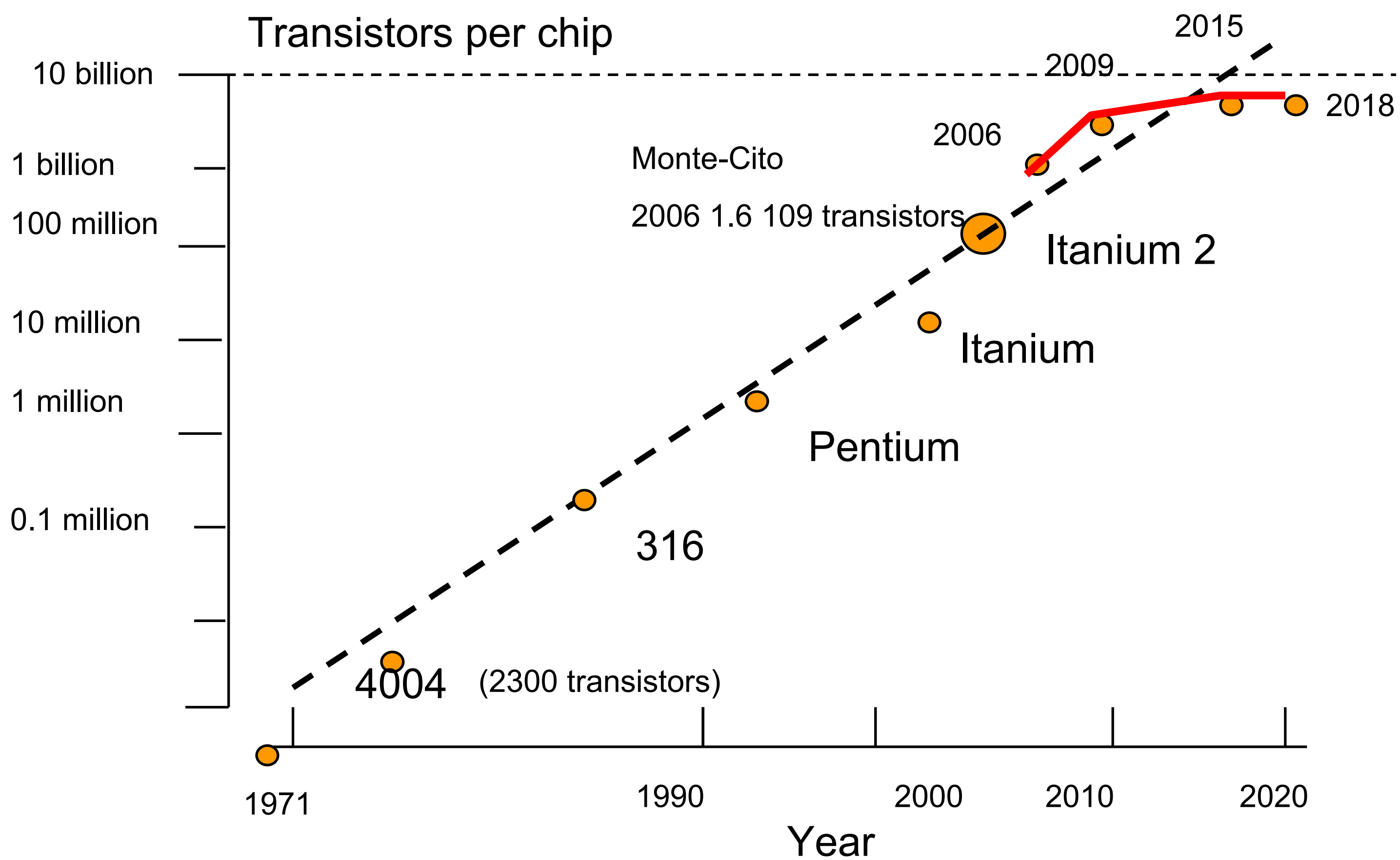
Gwyn Williams holding a 5-cell cavity inside JLab's FEL

CPU speed versus time



From D. A. Muller, A sound barrier for silicon? Nature Materials, 4, pp. 645-647 (2005).

VLSI Technology Limits: Moore No More



After http://www.indybay.org/uploads/2006/05/18/moore__sl_small.jpglsjprm.jpg

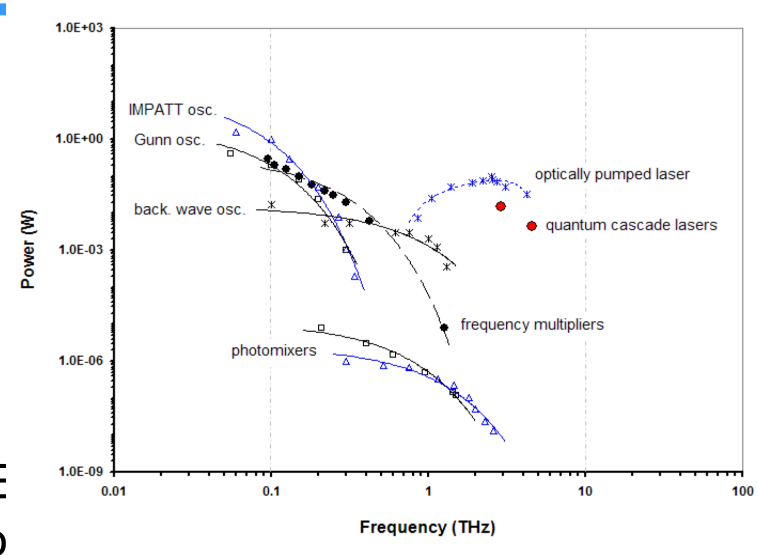
Tutorial Outline

- History
- Application examples
- Terahertz Photonics
- **Terahertz Electronics**
- Plasma wave electronics
- Terahertz properties of grainy multifunctional materials
- Conclusions and future work

Terahertz Electronics

- **Sources**
  - Two terminal devices
    - IMPATT
    - Gunn
  - Transistors
    - HEMTs
    - HBTs
    - Heterodimensional Transistors and FinFE
  - Plasma Wave Electronics emitters (laborato
  - Graphene THz lasers (proposed by V. Ryzhii)

30



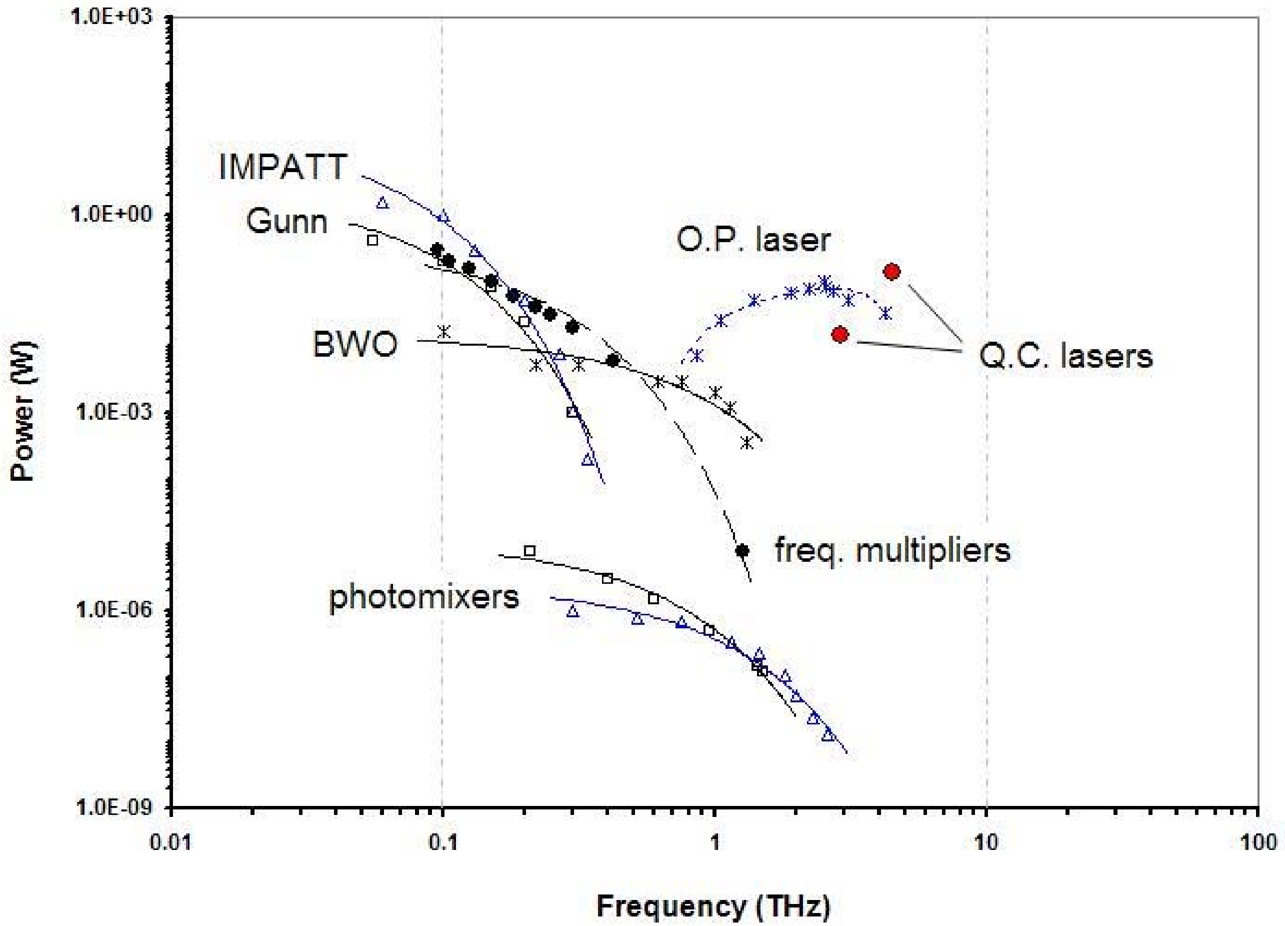
- **Detectors**
  - Schottky diodes
  - Pyroelectric detectors
  - Hot electron bolometers
  - Plasma Wave Detectors
    - Nonresonant
  - Carbon nanotubes (proposed)

Resonant Detectors

From W.J. Stillman and M.S. Shur, Closing the Gap: Plasma Wave Electronic Terahertz Detectors, Journal of Nanoelectronics and Optoelectronics, Vol. 2, Number 3, pp. 209-221, December 2007

THz gap

From W.J. Stillman and M.S. Shur, Closing the Gap: Plasma Wave Electronic Terahertz Detectors, Journal of Nanoelectronics and Optoelectronics, Vol. 2, Number 3, pp. 209-221, December 2007



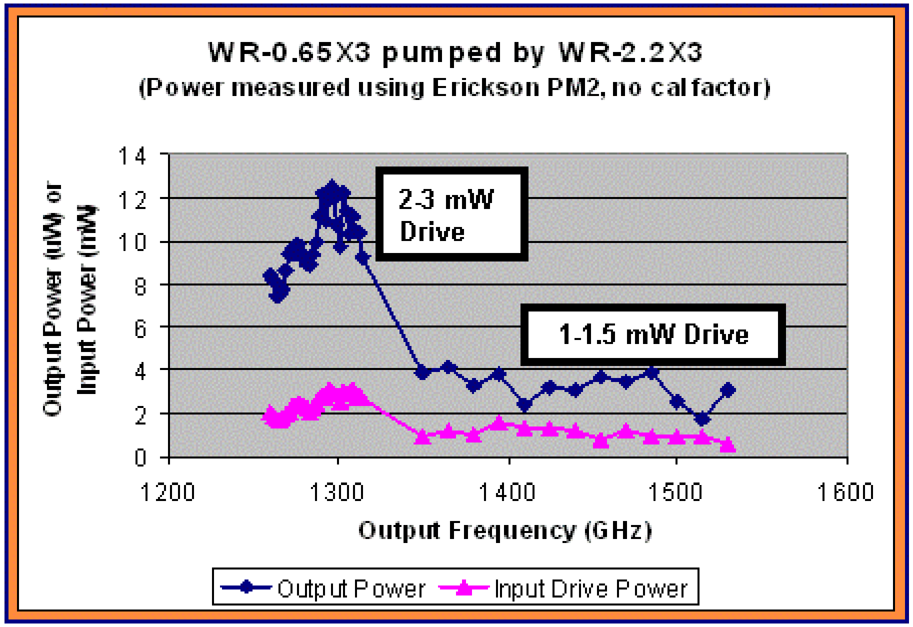
Schottky Diode Tripler

Virginia Diodes, Inc.

VDI Model: WR0.65x3

1100-1700 GHz Output, Full-band Frequency Tripler

- 0.3-0.5% Efficiency
- No Bias
- Planar construction
- Input flange: WR-2.0
- Output flange: Feedhorn
- Size: 1.2 x 0.8 x 0.25 inch

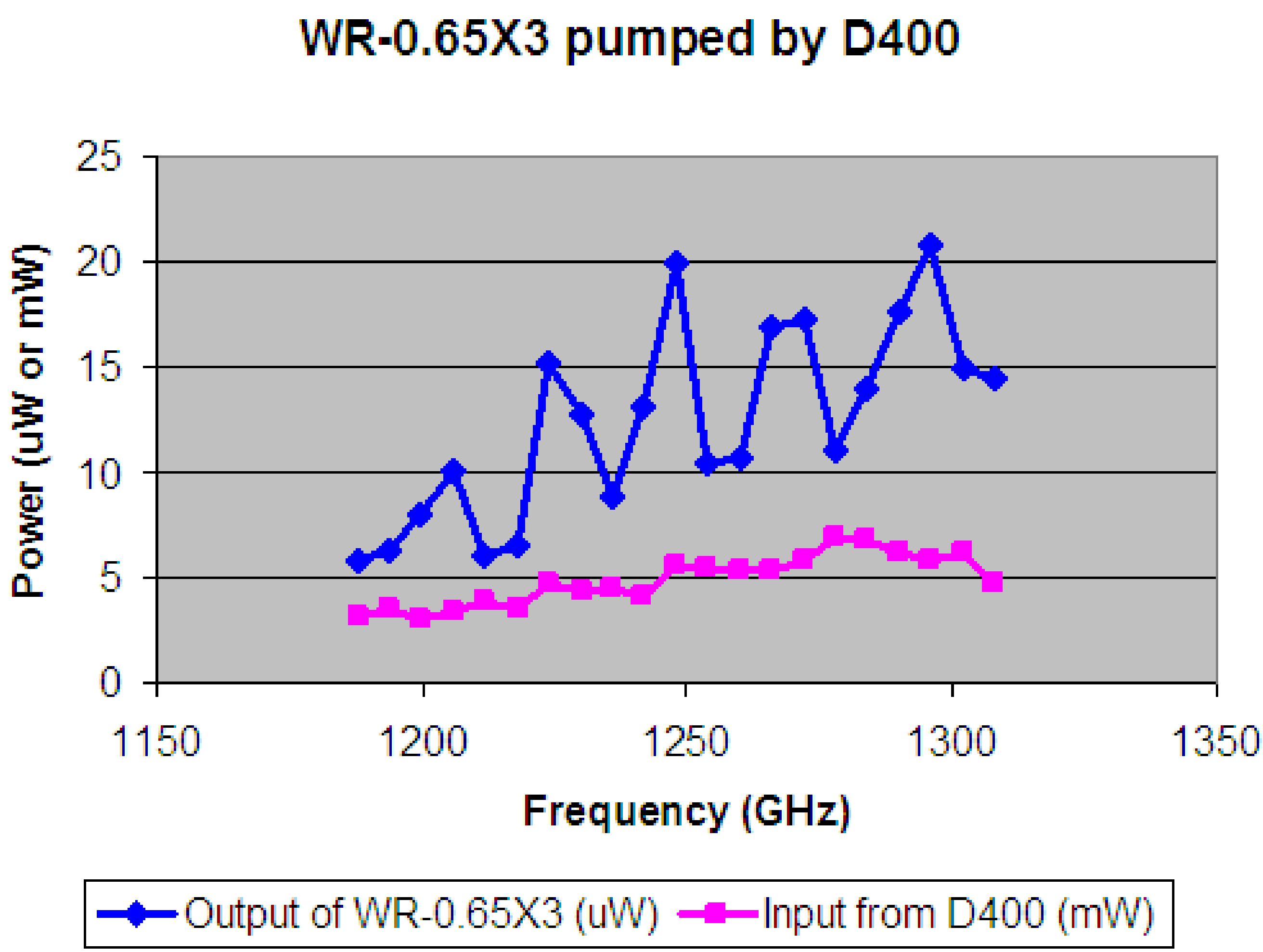


Contact VDI today for specifications and quotation details.

Virginia Diodes, Inc., Ph:434.297.3257, FAX:434.297.3258, www.virginiadiodes.com, VDIRFQ@virginiadiodes.com

Courtesy of Virginia Diodes, Inc. Reproduced with permission

Schottky Diode Multiplication



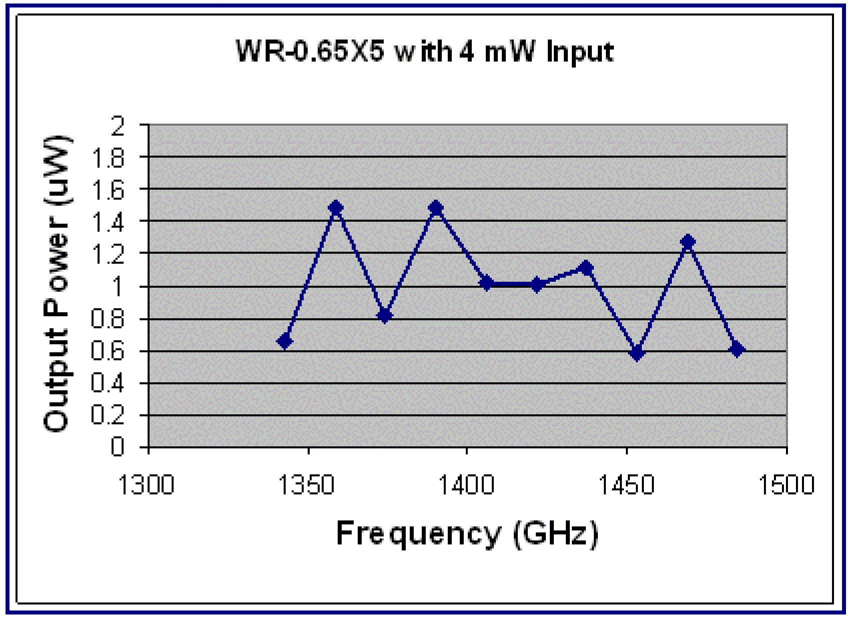
Courtesy of Virginia Diodes, Inc. Reproduced with permission.

Schottky Diode Quintupler

Virginia Diodes, Inc.

1.1-1.7 THz WR0.65x5 Quintupler

- No mechanical tuners
- Planar construction
- Efficiency: 0.025%



Contact VDI today for specifications and quotation details.

Virginia Diodes, Inc., Ph:434.297.3257, FAX:434.297.3258, www.virginiadiodes.com, VDIRFQ@virginiadiodes.com

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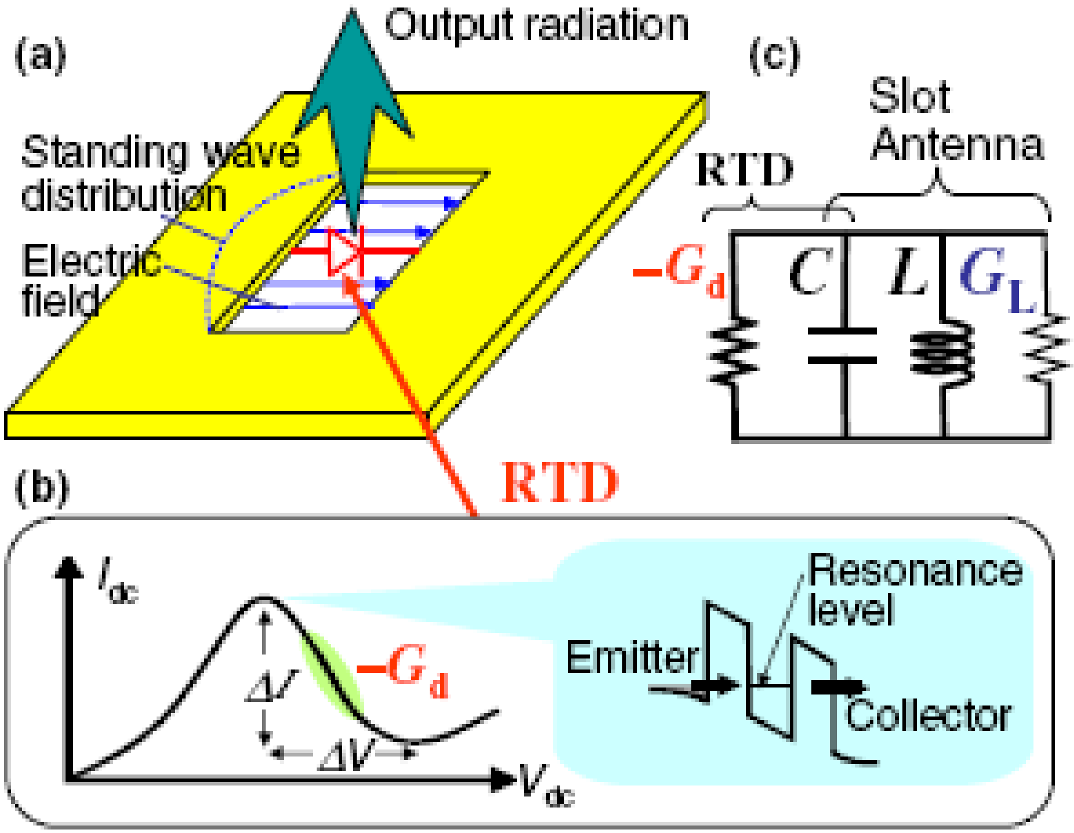
Resonant Tunneling Diodes



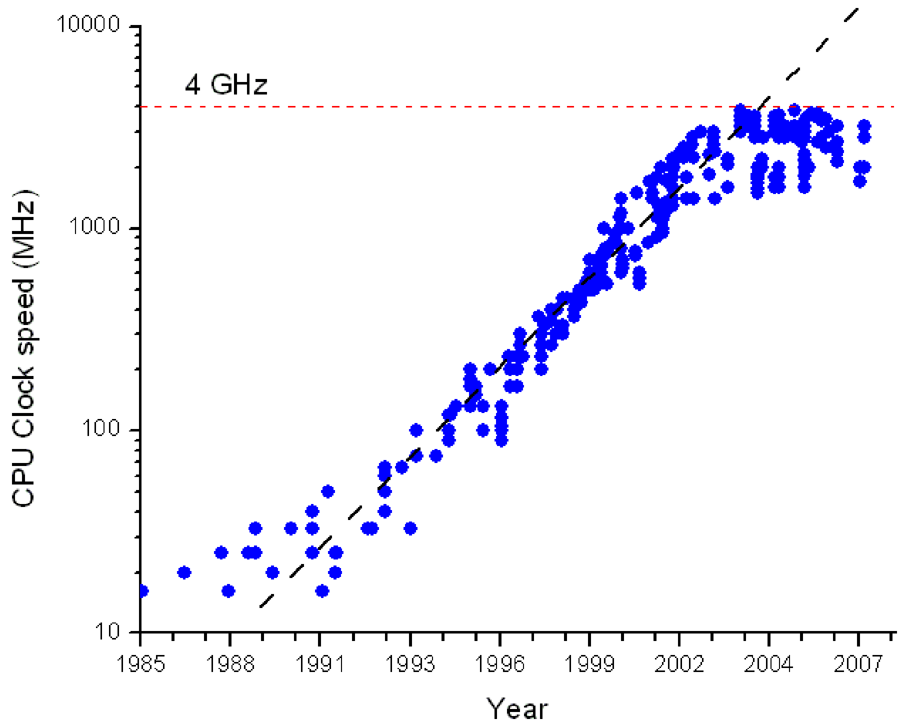
(Color online) Fundamental structure of the RTD oscillator. (a) Slot resonator and RTD, (b) potential profile and current–voltage characteristics of RTD, and (c) equivalent circuit of (a).

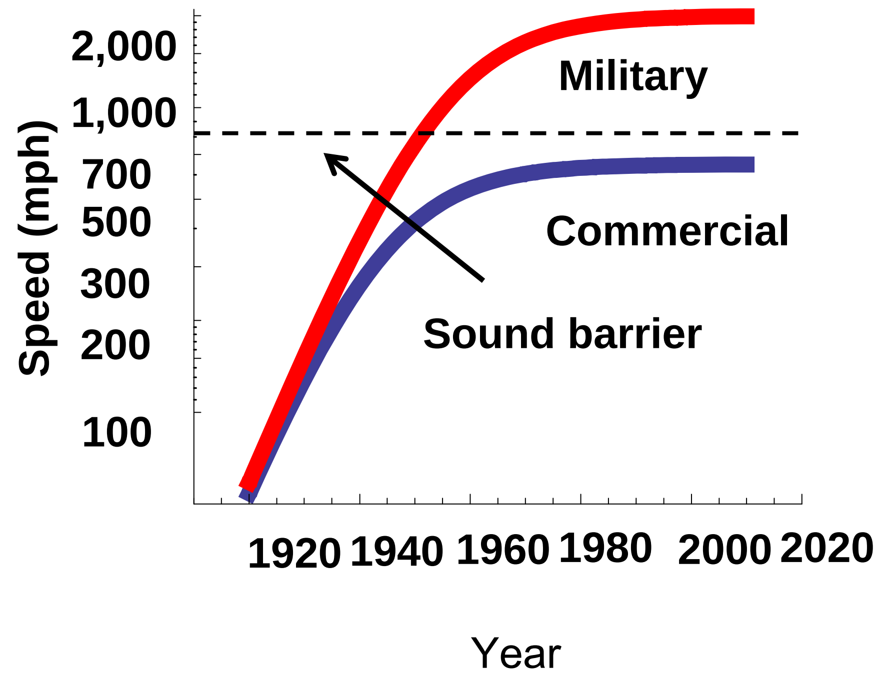
Fundamental oscillation up to 0.65 THz and harmonic oscillation up to 1.02 THz

From Masahiro ASADA, Safumi SUZUKI, and Naomichi KISHIMOTO "Resonant Tunneling Diodes for Sub-Terahertz and Terahertz Oscillators" Japanese Journal of Applied PhysicsVol. 47, No. 6, 2008, pp. 4375–4384

Expected up to 60 microwatt at 2 THz

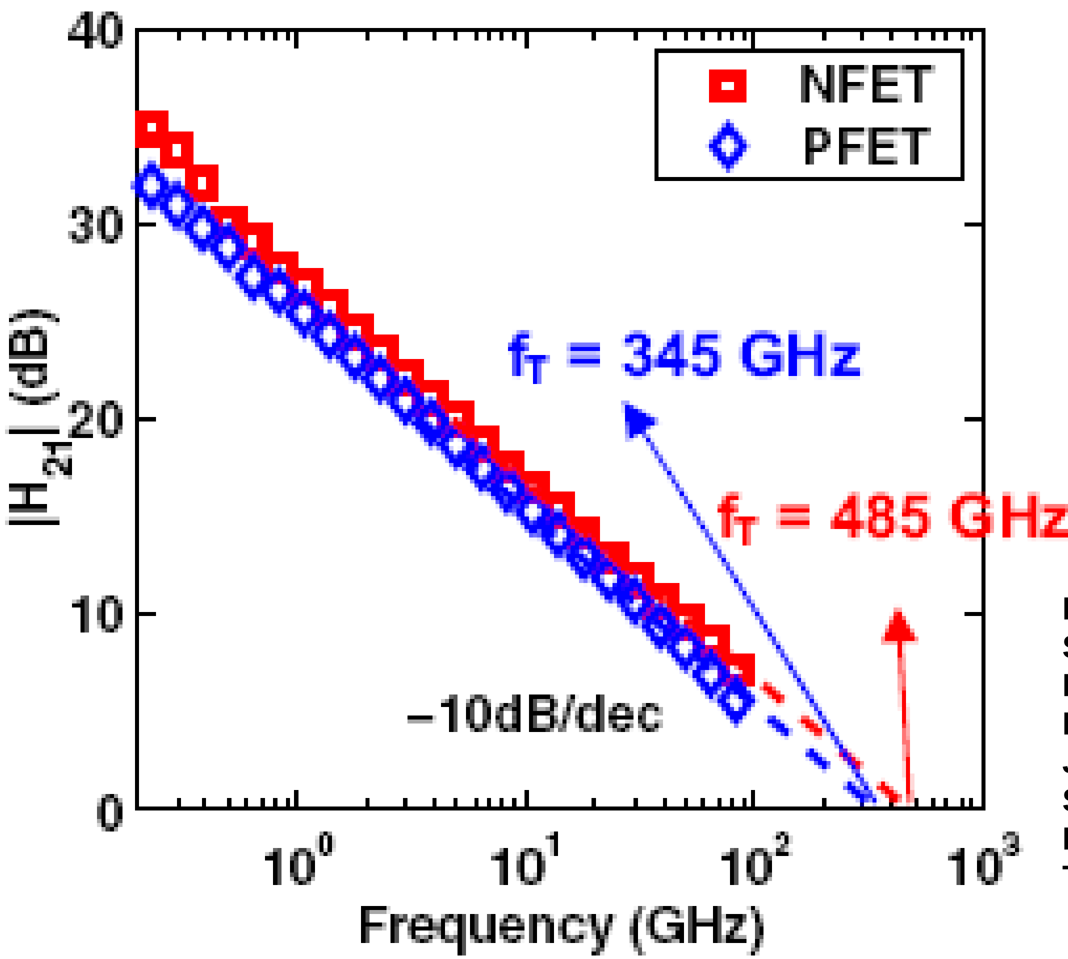
CPU Clock Speed versus Year





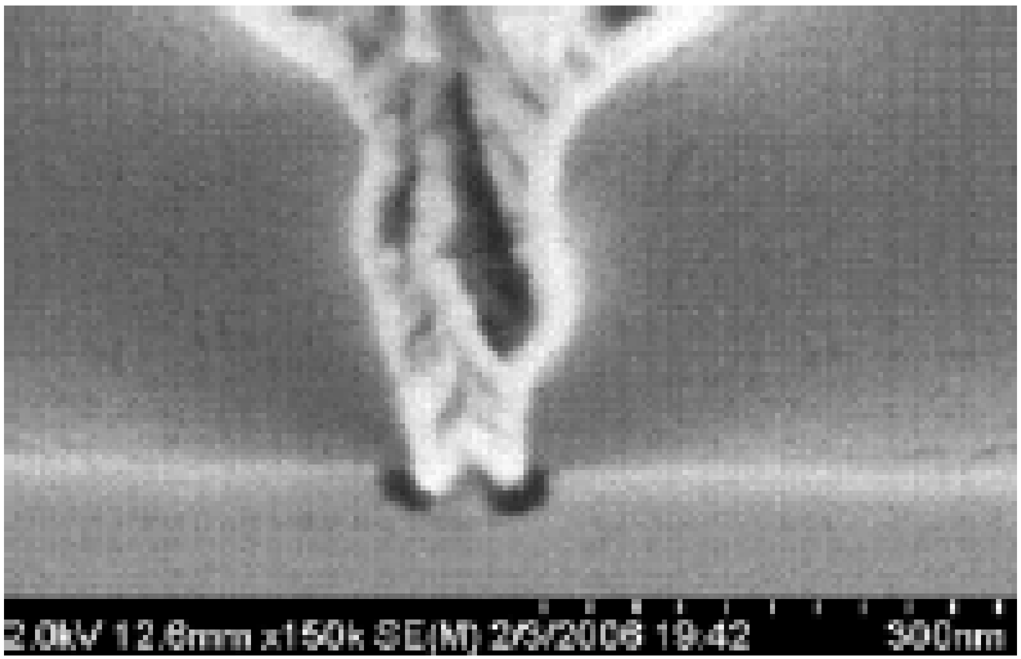
From http://ask.metafilter.com/78227/

45nm IBM Si NMOS and PMOS using a notched body contact



From Sungjae Lee, Basanth Jagannathan*, Shreesh Narasimha*, Anthony Chou*, Noah Zamdmer*, Jim Johnson, Richard Williams, Lawrence Wagner*, Jonghae Kim*, Jean-Olivier Plouchart*, John Pekarik, Scott Springer and Greg Freeman, Record RF performance of 45-nm SOI CMOS Technology, IEDM Technical Digest, p. 225 (2007)

Northrop Grumman fmax is higher than 1 THz



From R. Lai, X. B. Mei, W.R. Deal, W. Yoshida, Y. M. Kim, P.H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, A. Fung, Sub 50 nm InP HEMT Device with Fmax Greater than 1 THz, IEDM Technical Digest, p. 609 (2007)

InGaAs/InP Based HEMT

35 nm gate device cross section

HRL 300 GHz MMIC

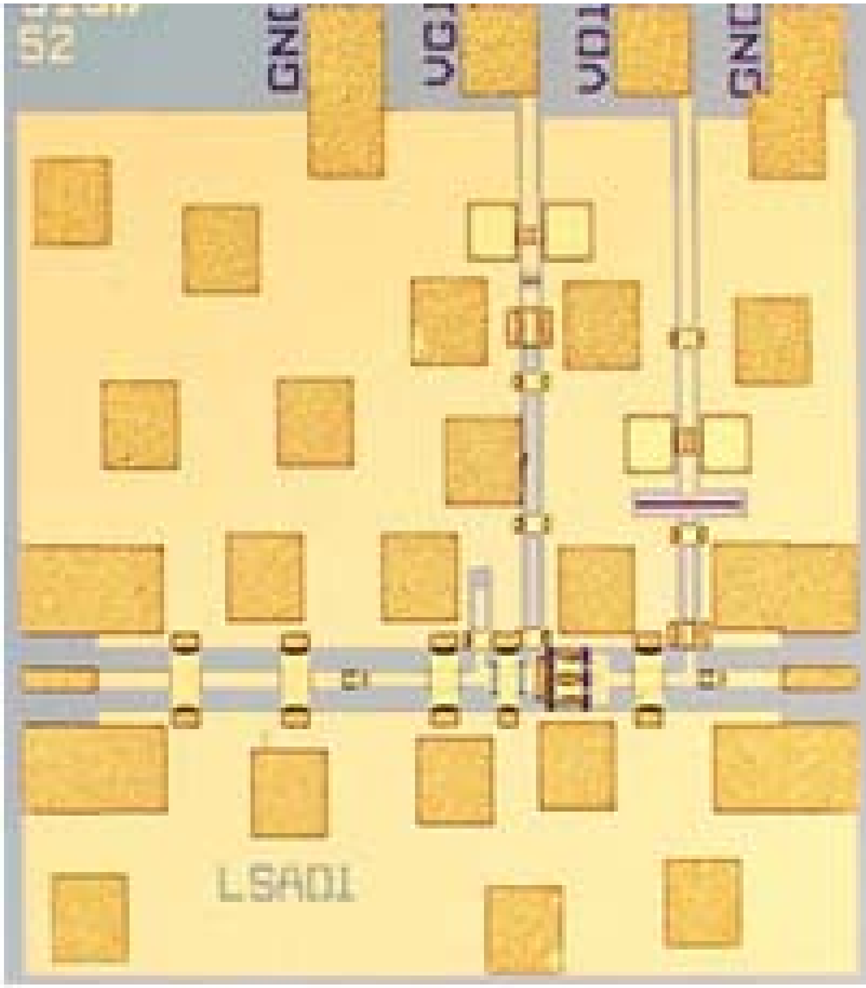


Figure 3. InP HEMT MMIC active doubler that demonstrated 100 microwatts of output power at 300 GHz.

From:
http://www.hrl.com/html/techs_mel.html

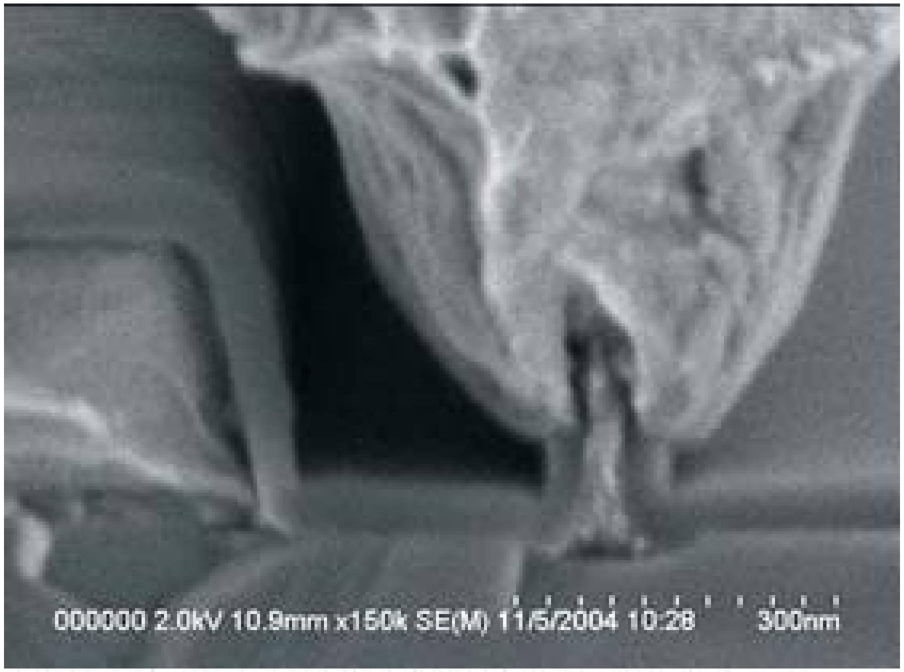
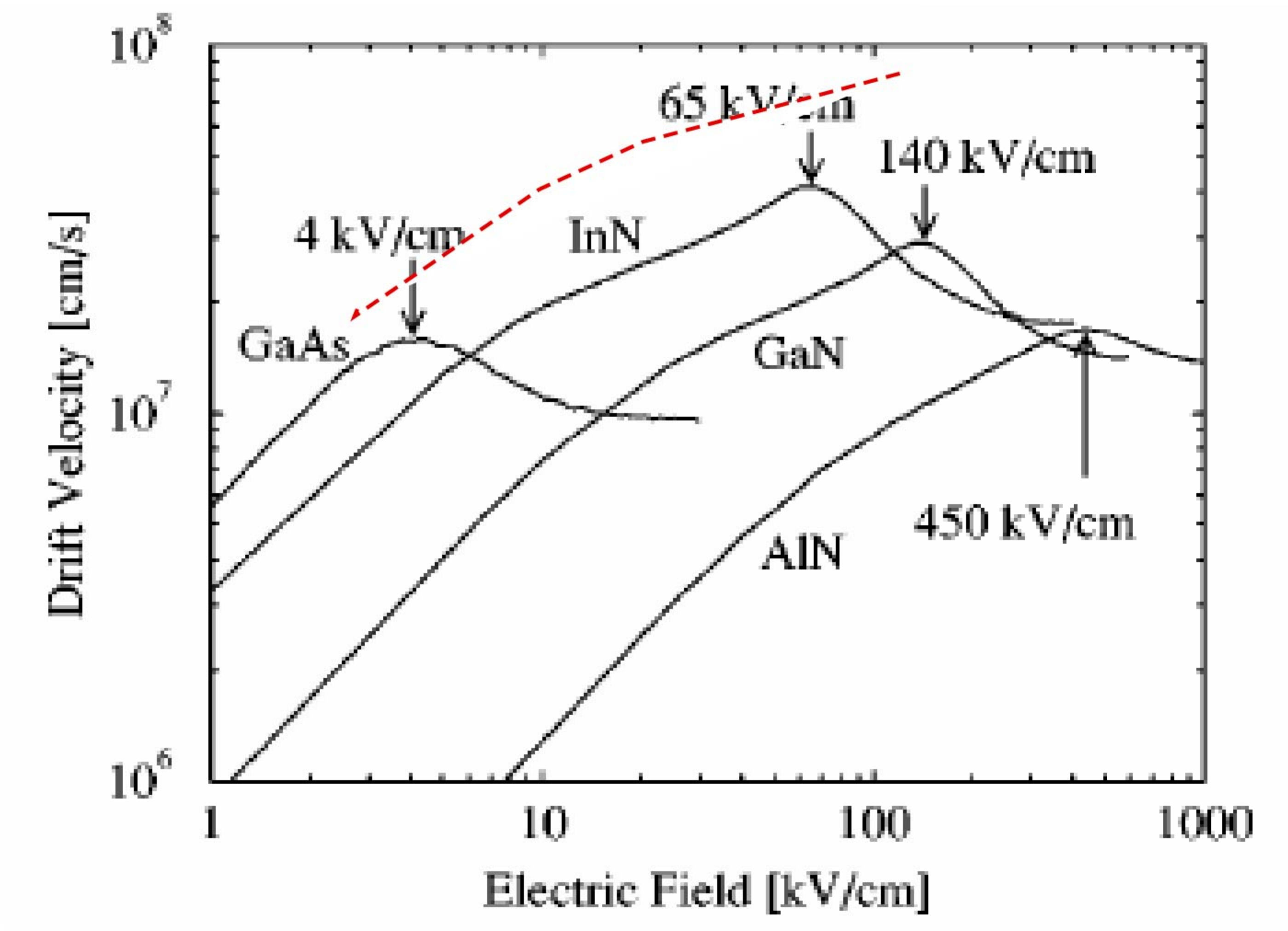


Figure 4. Scanning electron micrograph of a HEMT T-gate structure showing a metal gate footprint of approximately 50 nanometers encapsulated in dielectric material. Similar structures can be used for various quantum and spin-based devices.

Velocity-Field Curves for III-N Family



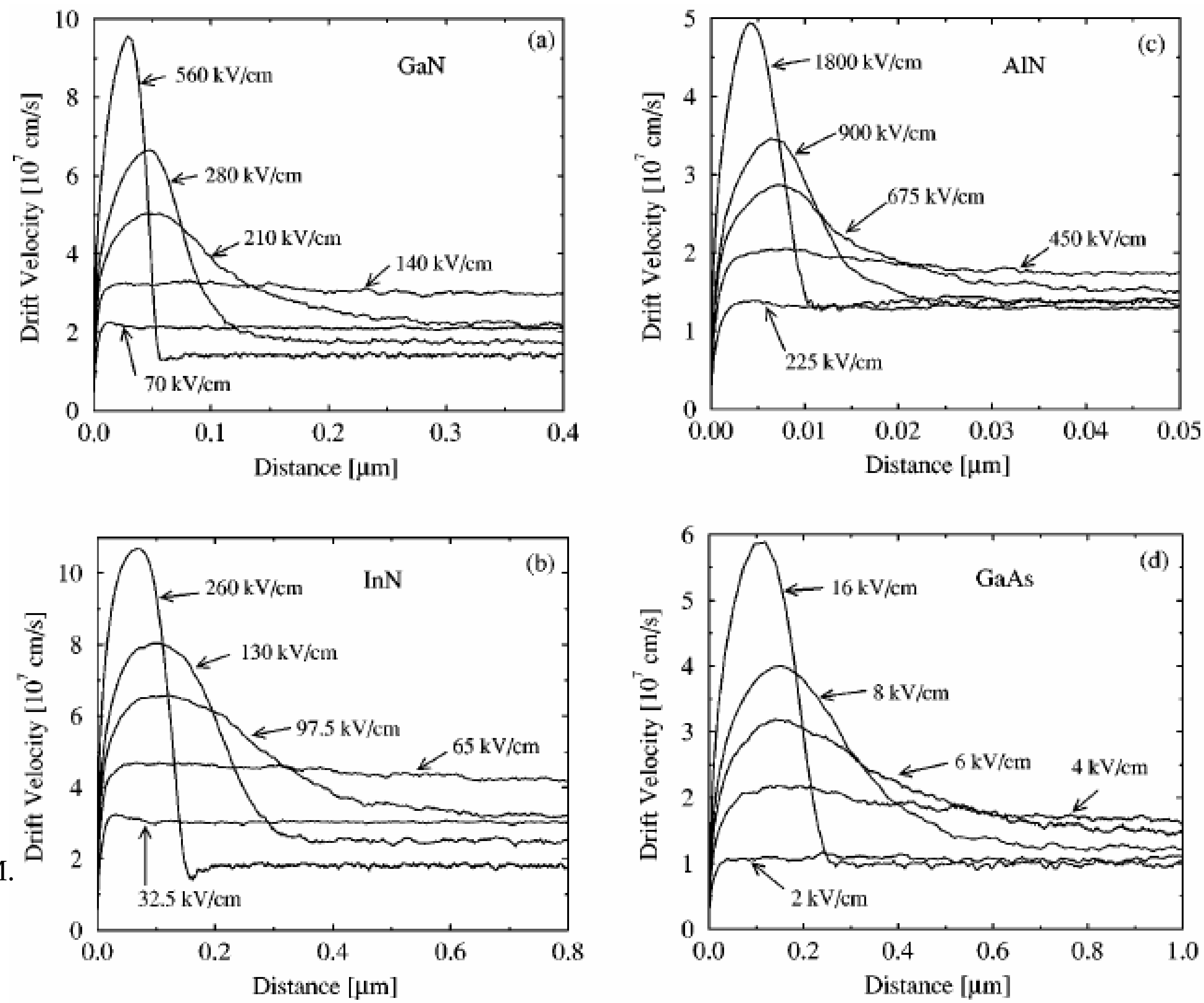
From B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman, *J. Appl. Phys.* **85**, 7727 (1999)

InN is the fastest nitride material

Red Line – v(E) for InAs (from Hess and Brennan (1984), See **M.P. Mikhailova *Handbook Series on Semiconductor Parameters*, vol.1, M. Levinshtein, S. Rumyantsev and M. Shur, ed., World Scientific, London, 1996, pp. 147-168.**

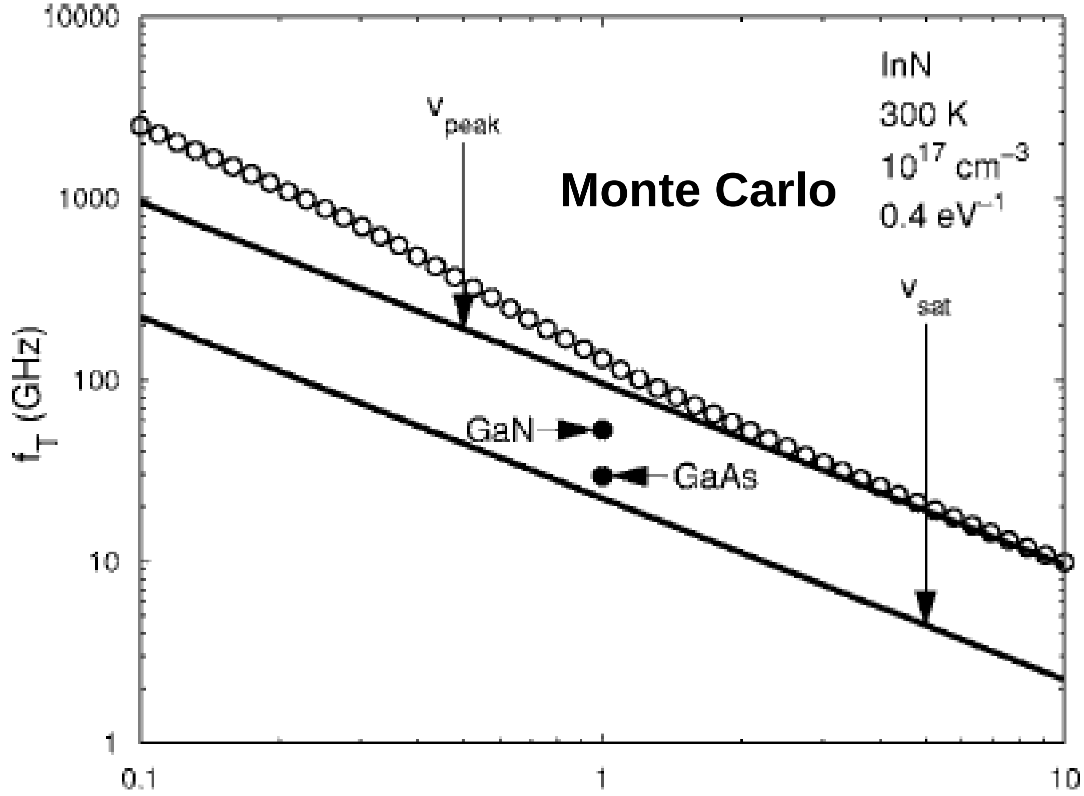
Higher velocity in short devices - overshoot

InN – higher overshoot at smaller fields



From B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman, *J. Appl. Phys.* **85**, 7727 (1999)

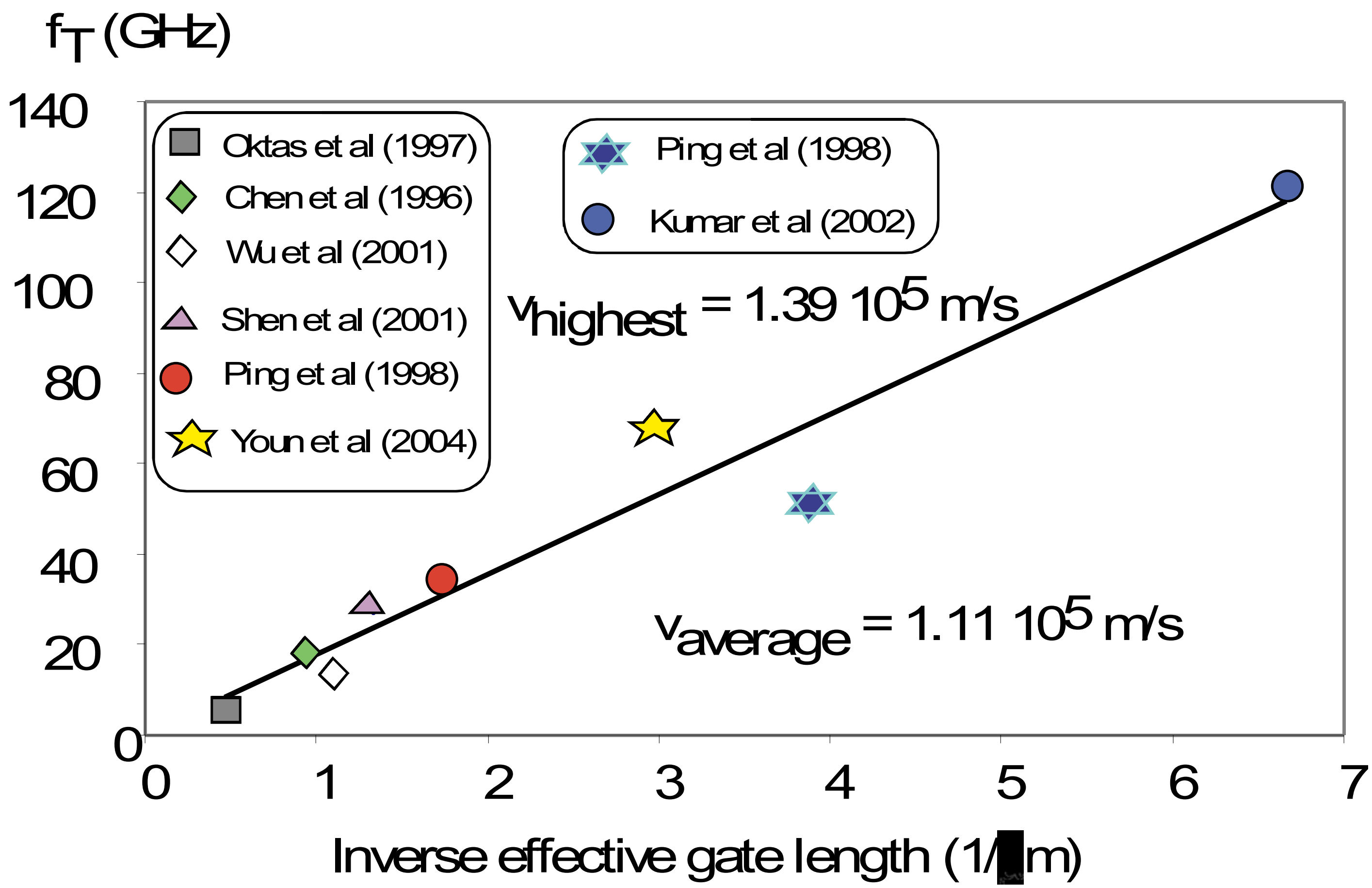
Calculated Cutoff Frequency



Channel length (micron)

From S. K. O'Leary, B. E. Foutz, M. S. Shur, and L. F. Eastman,
Potential Performance of Indium-Nitride-based Devices, Appl. Phys. Lett. 88, 152113 (2006)

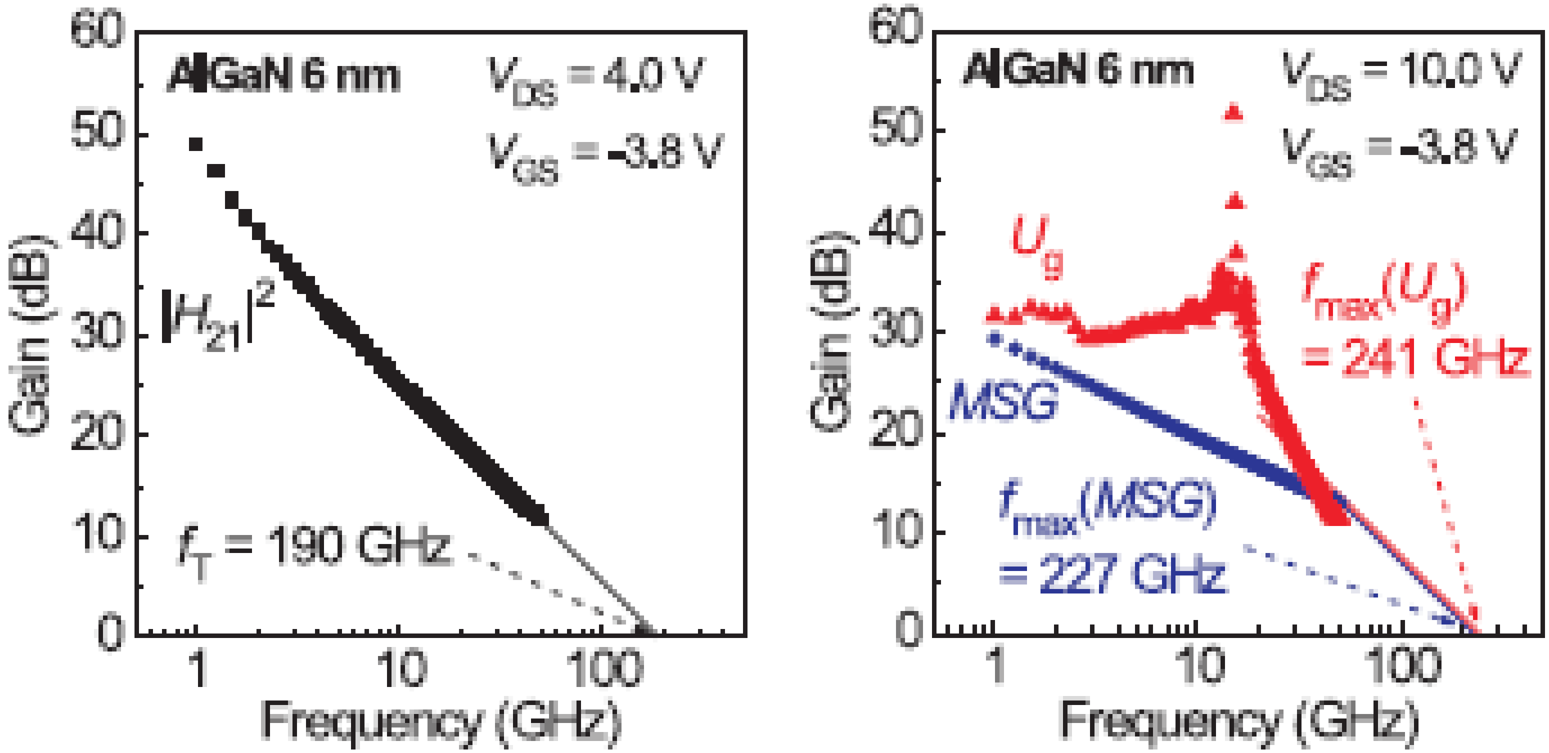
Cutoff frequency and effective velocity GaN



From M. S. Shur and R. Gaska, Physics of GaN-based Heterostructure Field Effect Transistors, 2005 IEEE CSICS Technical Digest, Palm Springs, CA, pp. 137-140, ISBN 0-7803-9250-7

RECORD!

60 nm GaN-HEMT from Fujitsu



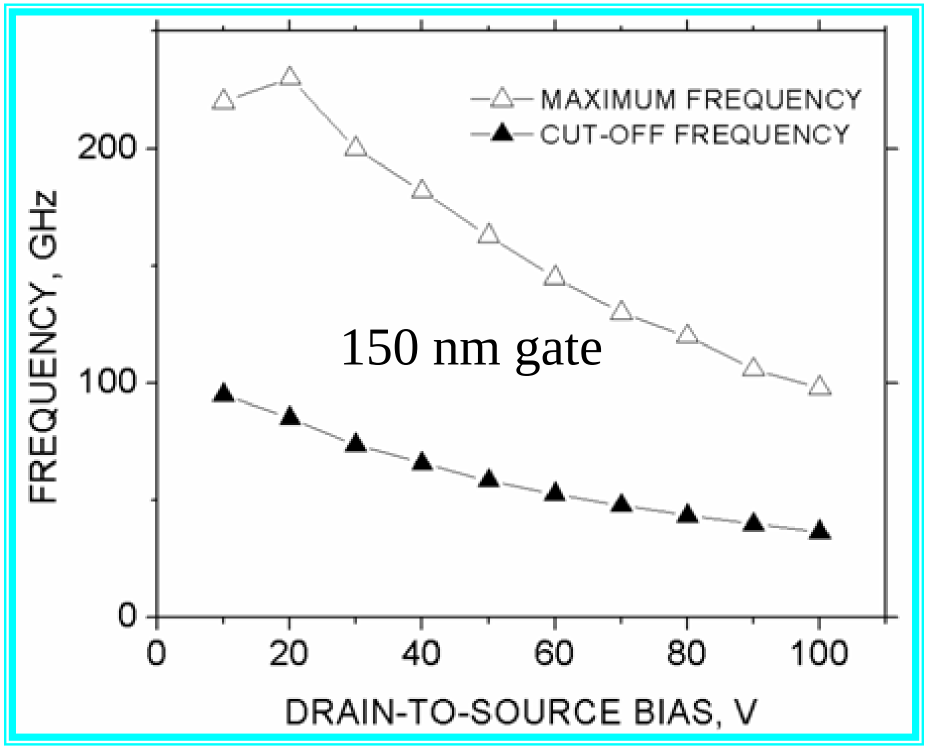
Applied Physics Express **1** (2008) 021103

AlGaN/GaN Heterostructure Field-Effect Transistors on 4H-SiC Substrates with Current-Gain Cutoff Frequency of 190 GHz

Masataka Higashiwaki[1*], Takashi Mimura[1,2], and Toshiaki Matsui[1]

Nitride Problem: Effective Gate Length

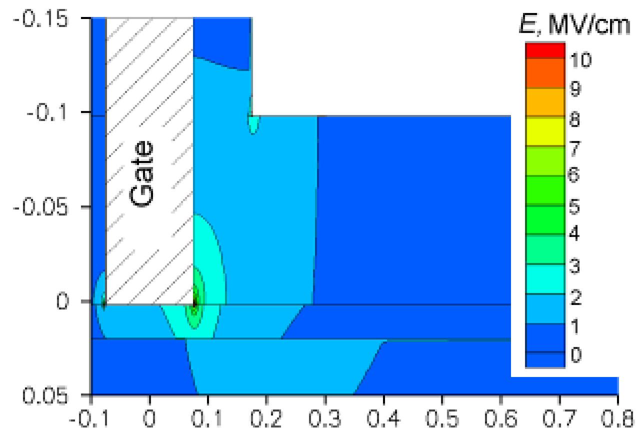
- THz-range transistors require gate electrodes with deep submicron-length
- Effective gate length significantly exceeds the physical gate length
- As a result, high cut-off frequencies can only be achieved at low drain bias ⇨ low RF-powers
- At high drain bias effective gate length increases ⇨ lower cut-off frequencies

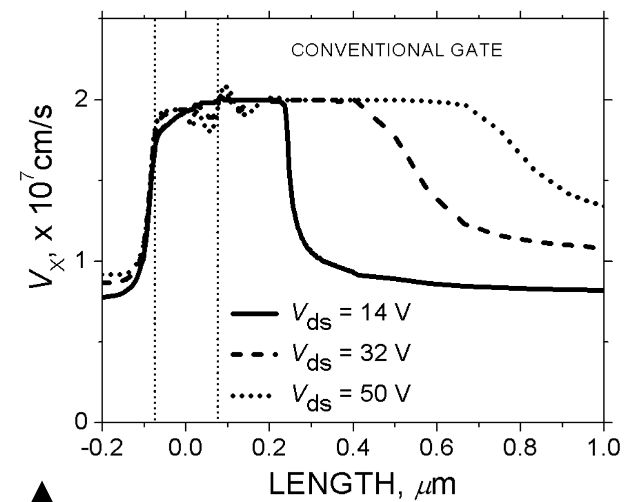


From V. Turin, M. Shur, D. Veksler, International Journal of High Speed Electronics and Systems, vol. 17, No. 1, 19, 2007

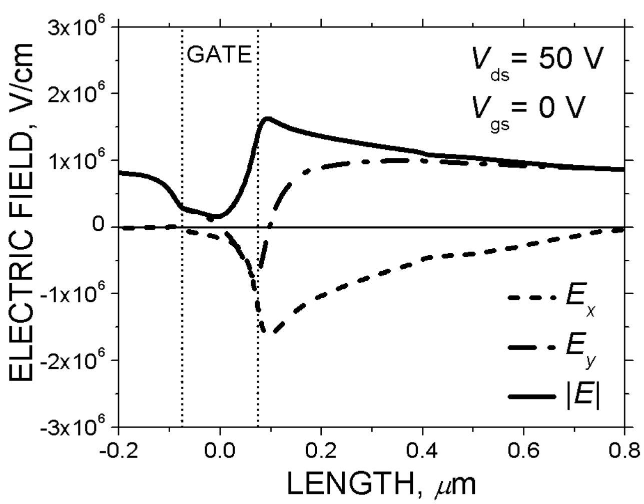
EFFECTIVE GATE LENGTH

After V. O. Turin, M. S. Shur, and D. B. Veksler, IJHSES, vol. 17, No. 1, 19, 2007



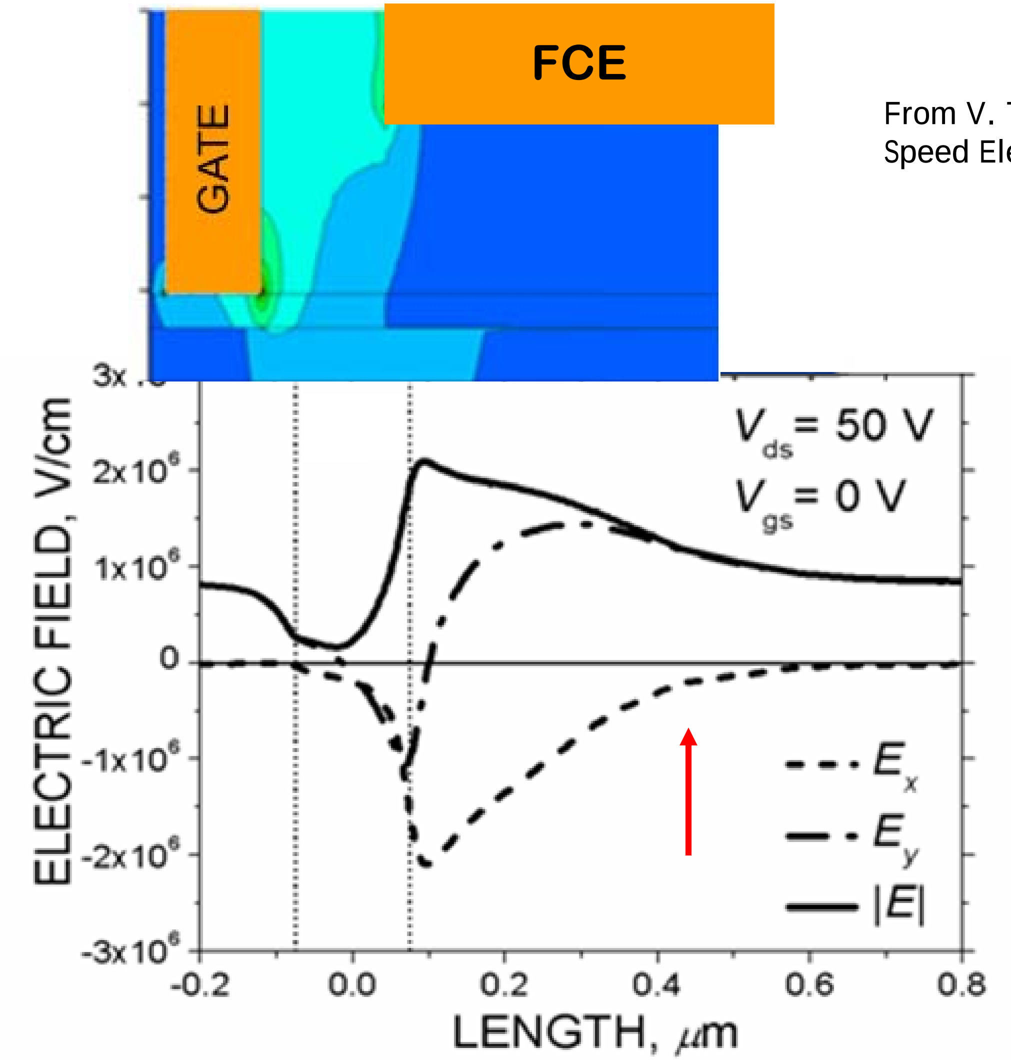


Distribution of electron velocity in the channel under the gate (1 nm below AlGaN-GaN interface)



Distribution of electric field in the channel under the gate

Drain Field Controlling Electrode (FCE)

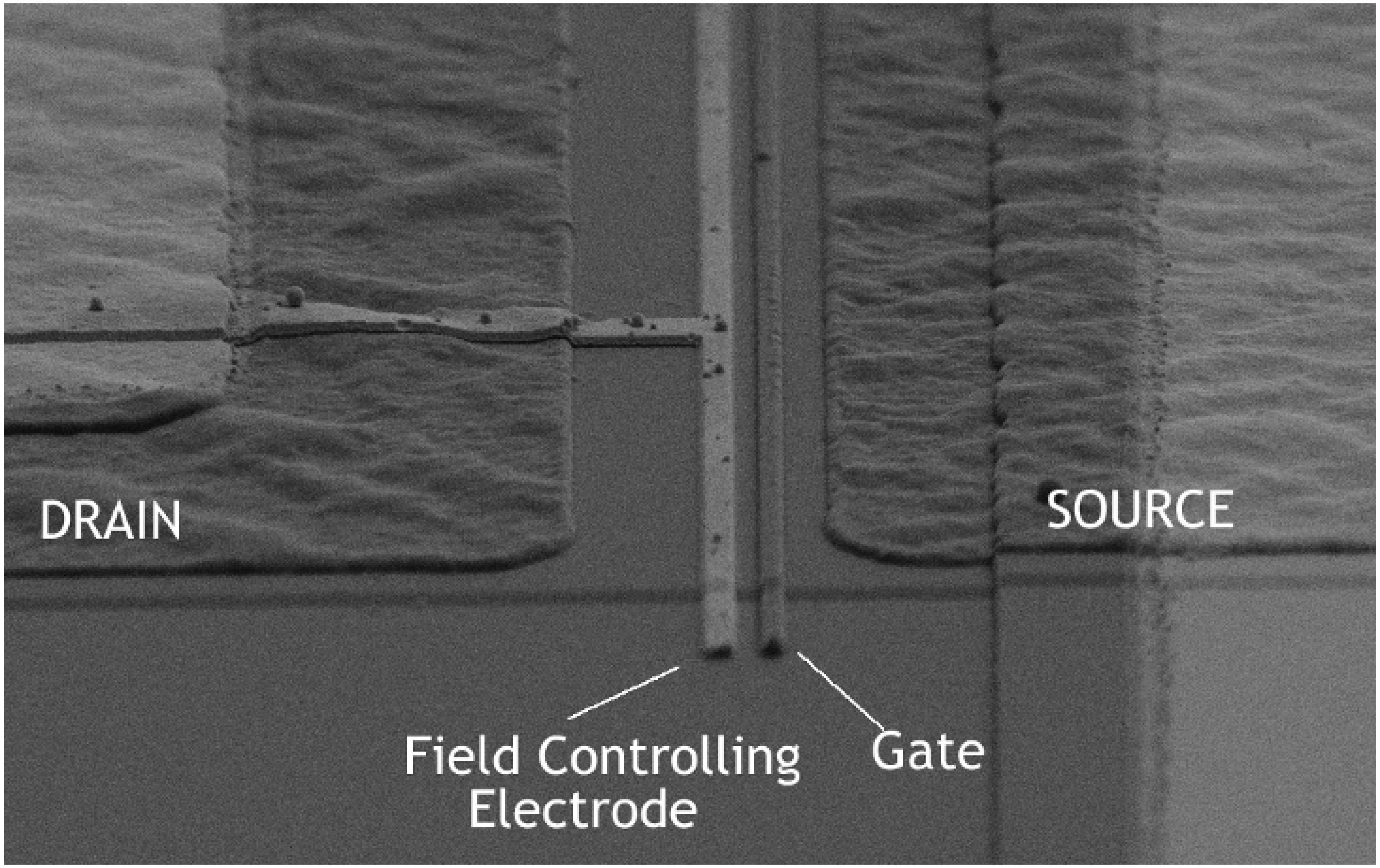


From V. Turin, M. Shur, D. Veksler, International Journal of High Speed Electronics and Systems, March 2007

FCE connected to the drain with small gap between the gate can be used to influence electron velocity distribution in channel that, in turn, can improve the cutoff frequency.

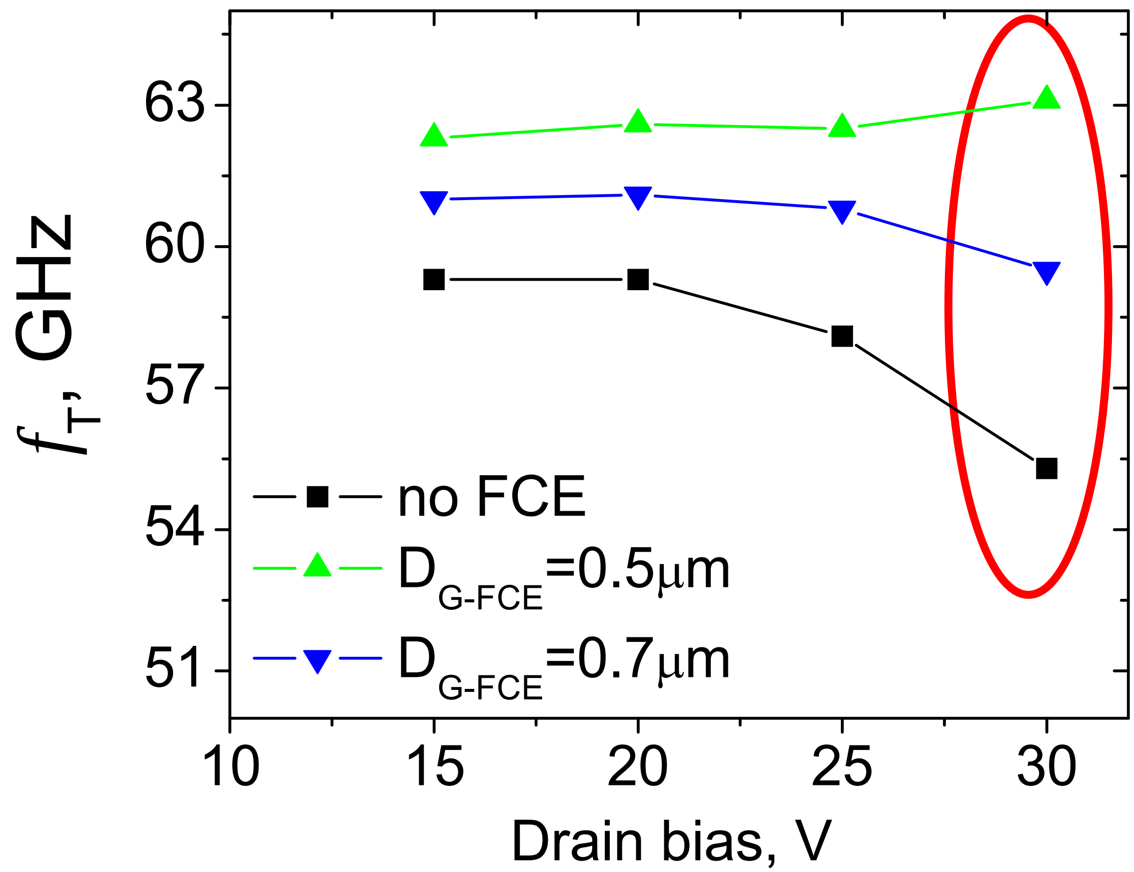
After V. O. Turin, M. S. Shur, and D. B. Veksler Simulations of field-plated and recessed gate gallium nitride-based heterojunction field-effect transistors, International Journal of High Speed Electronics and Systems, vol. 17, No. 1 pp. 19-23 (2007)

Field Controlling Electrode Implementation



After Pala, N. Yang J., Z. Koudymov, A. Hu, X. Deng, J. Gaska, R. Simin, G. Shur, M. S. Drain-to-Gate Field Engineering for Improved Frequency Response of GaN-based HEMTs, Device Research Conference 2007 65th Annual, 18-20 June 2007, pp. 43-44

Improvement of f_T

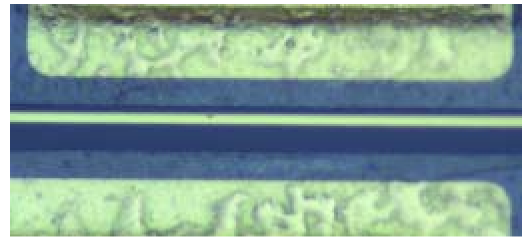


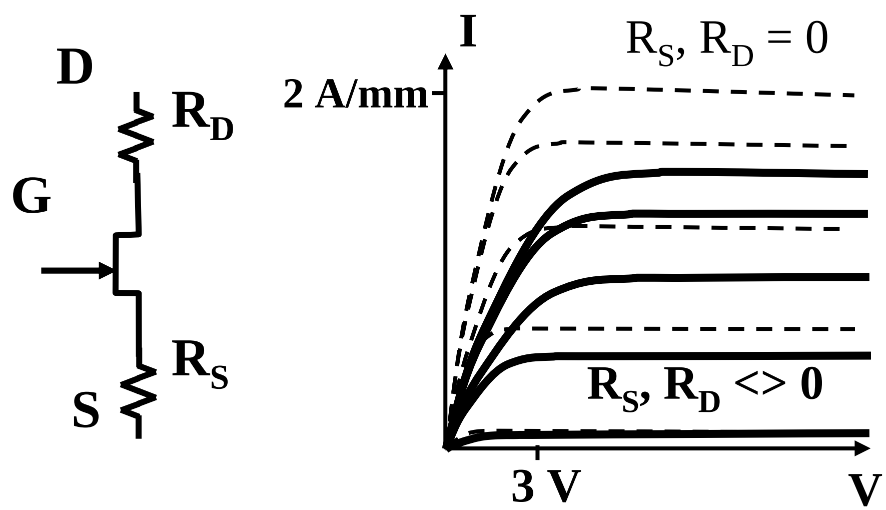
L_g=0.3 μm

After Pala, N. Yang J., Z. Koudymov, A. Hu, X. Deng, J. Gaska, R. Simin, G. Shur, M. S. Drain-to-Gate Field Engineering for Improved Frequency Response of GaN-based HEMTs, Device Research Conference 2007 65th Annual, 18-20 June 2007, pp. 43-44

Problem: Access Resistances

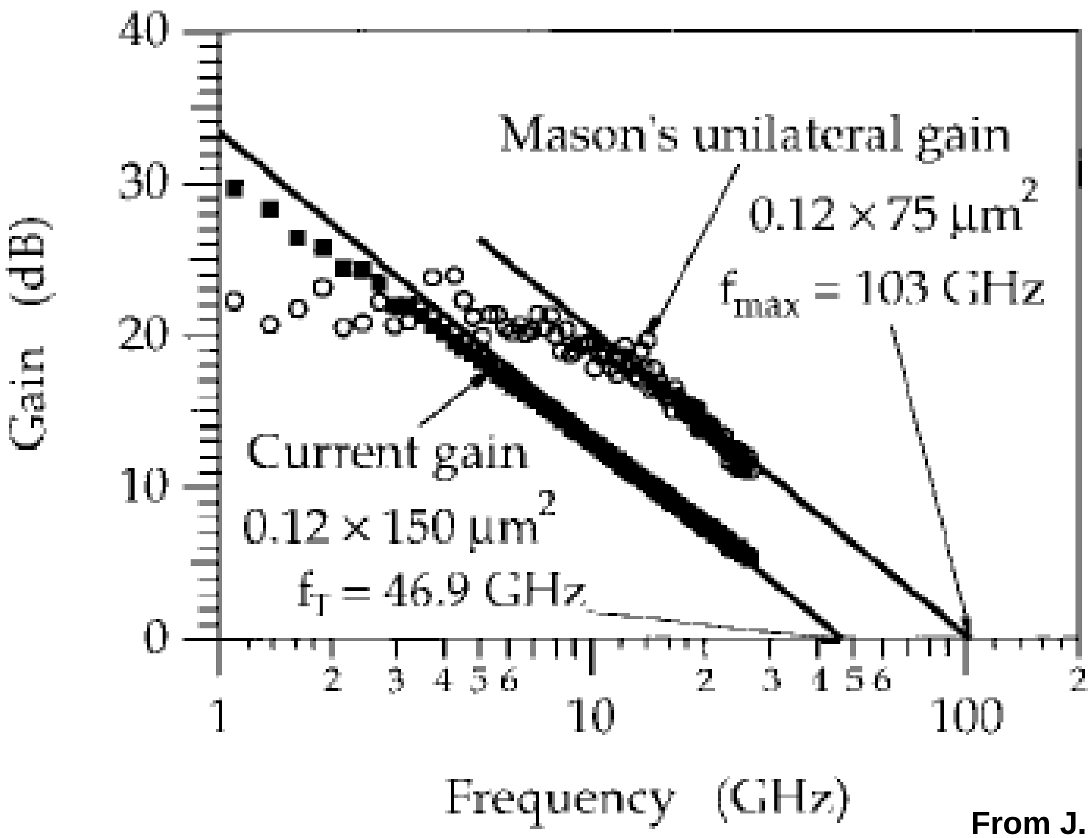
- THz-range transistors require highest possible RF transconductance.
- Source resistance drastically reduces the transconductance of devices with sub-mm long gate. Hence extremely low contact and source-gate access resistances are required.
- Annealed contacts do not allow for short source – drain spacing and have relatively high contact resistance





From G. Simin, Wide Bandgap Devices with Non-Ohmic Contacts, 210th Electrochemical Society Meeting 2006, Cancun, Mexico October 29-November 3, 2006

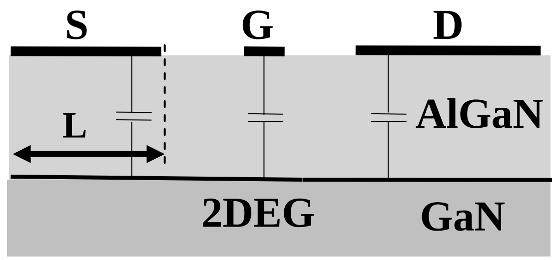
High fmax/ft are possible with high Rs using capacitive (C^3)contacts

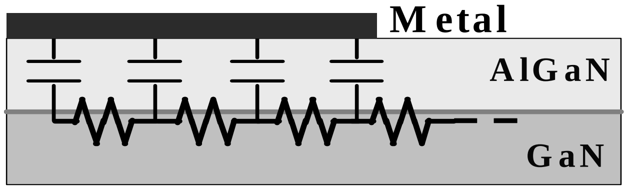


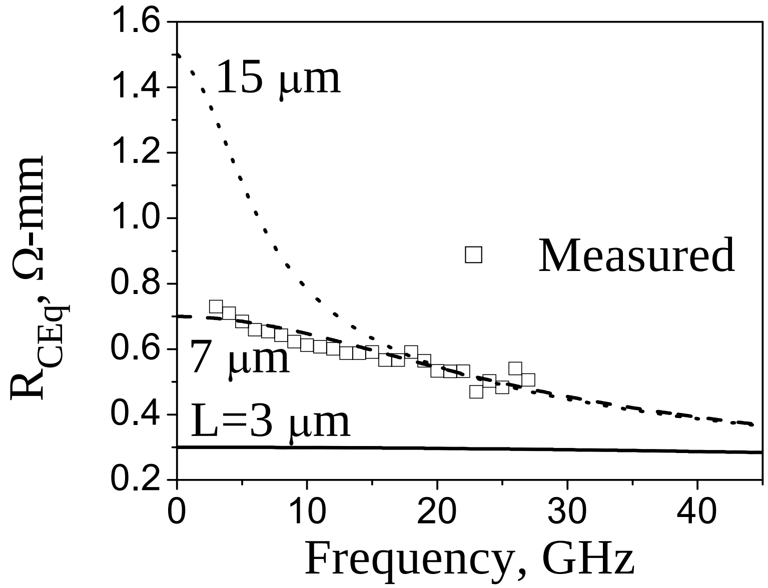
First evidence:
Rs was 10 ohm-mm!
Contacts were RC type (Schottky)

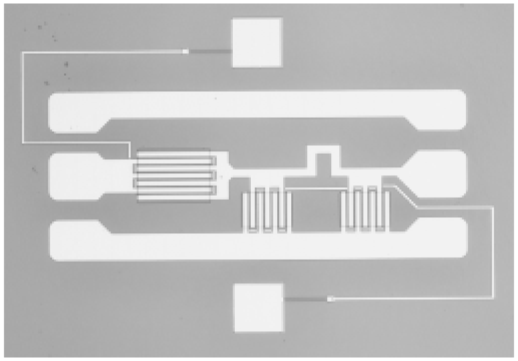
From J. Burm, K. Chu, W. J. Schaff, L. F. Eastman, M. A. Khan, Q. Chen, J. W. Yang, and M. S. Shur 0.12-µm Gate III-V Nitride HFET's with High Contact Resistances, IEEE Electron Device Letters, Vol. 18, No. 4, pp. 141-143, April (1997)

PROPOSED SOLUTION – C^3 CONTACTS + MIS



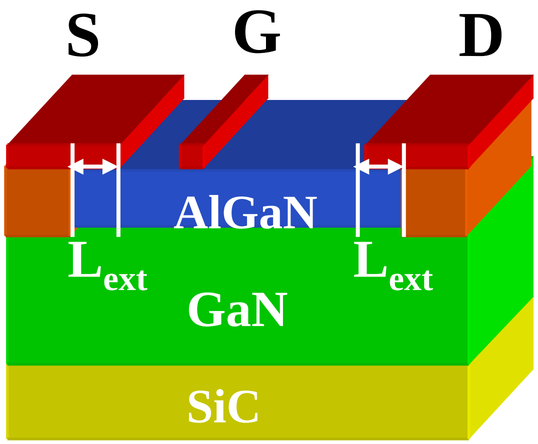


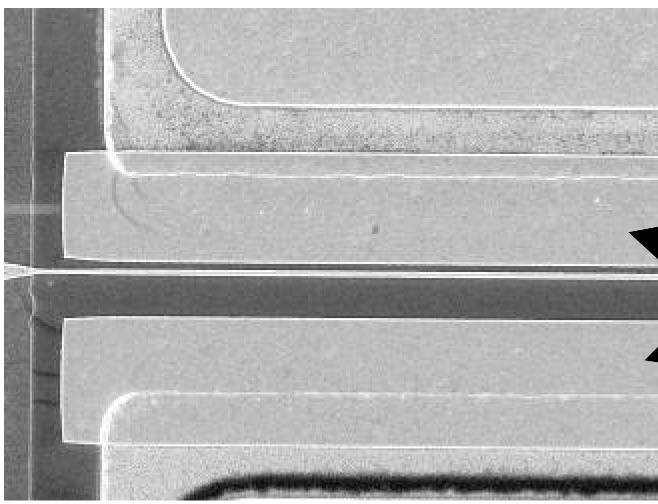


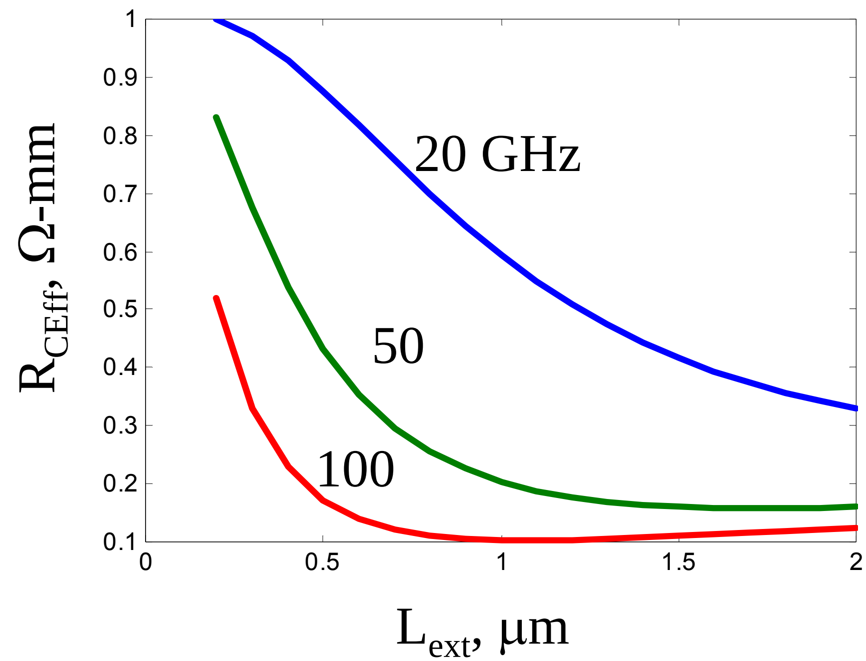


From Simin, G., Yang, Z-J. Shur, M.,, Microwave Symposium, 2007. IEEE/MTT-S 3-8 June 2007 pp. 457-460, ISSN: 0149-645X, ISBN: 1-4244-0688-9

PROPOSED SOLUTION – C^3 CONTACTS



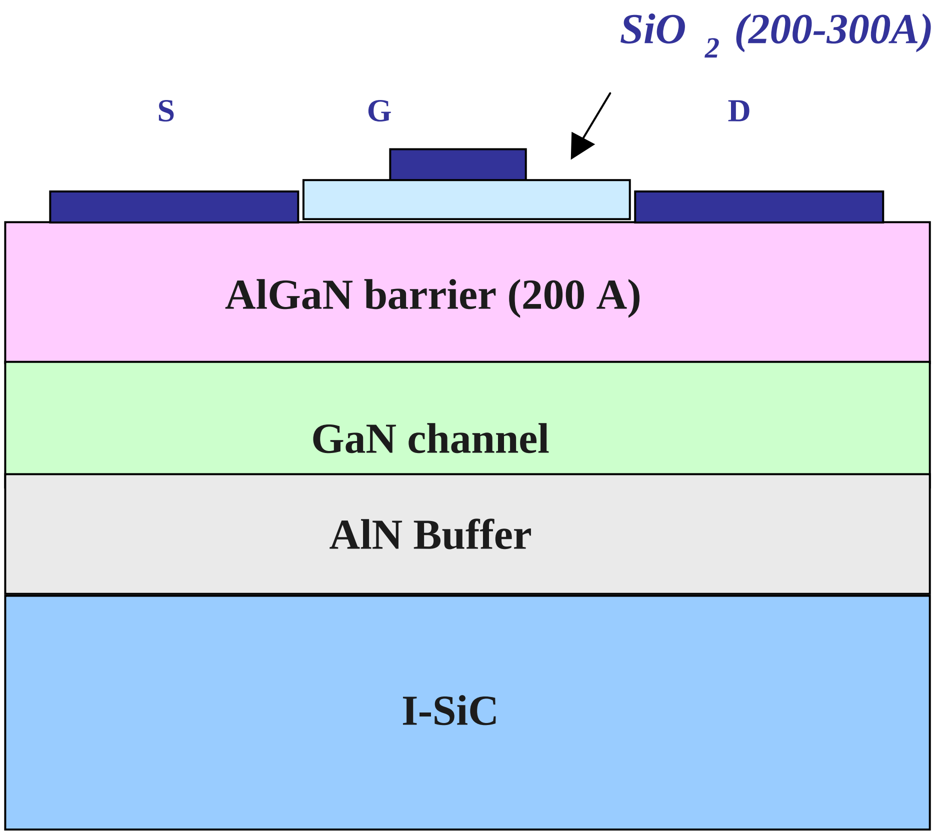


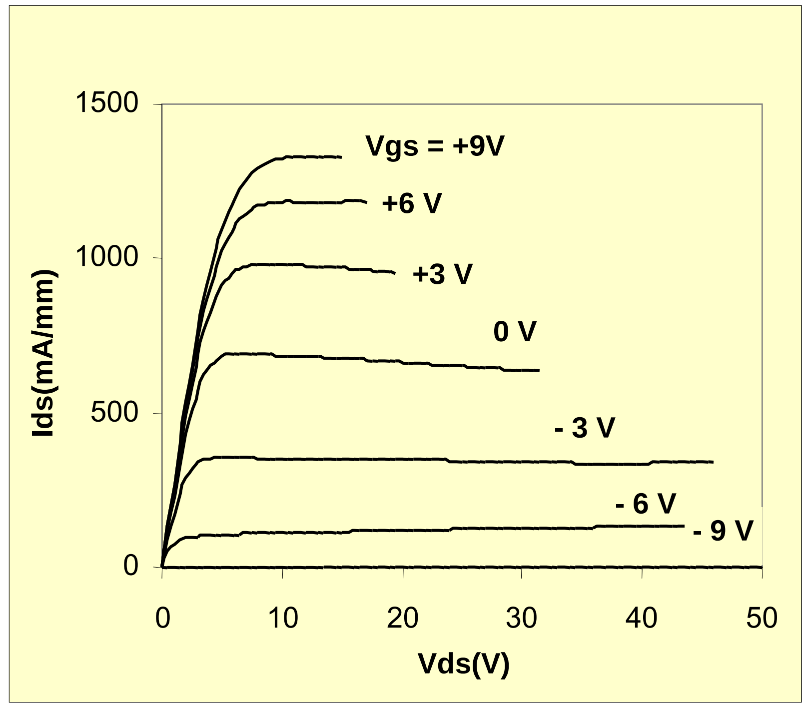


Self-aligned C^3 electrodes written and deposited simultaneously with gate

From G. Simin, Wide Bandgap Devices with Non-Ohmic Contacts, 210th Electrochemical Society Meeting 2006, Cancun, Mexico October 29-November 3, 2006

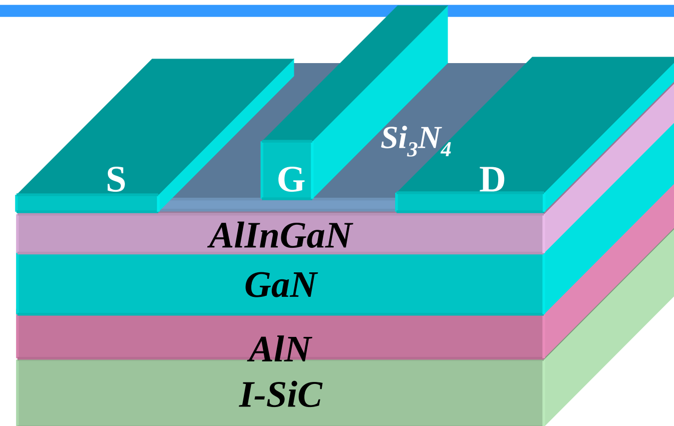
SiO_2/AlGaN/GaN Devices (MOSHFETs)





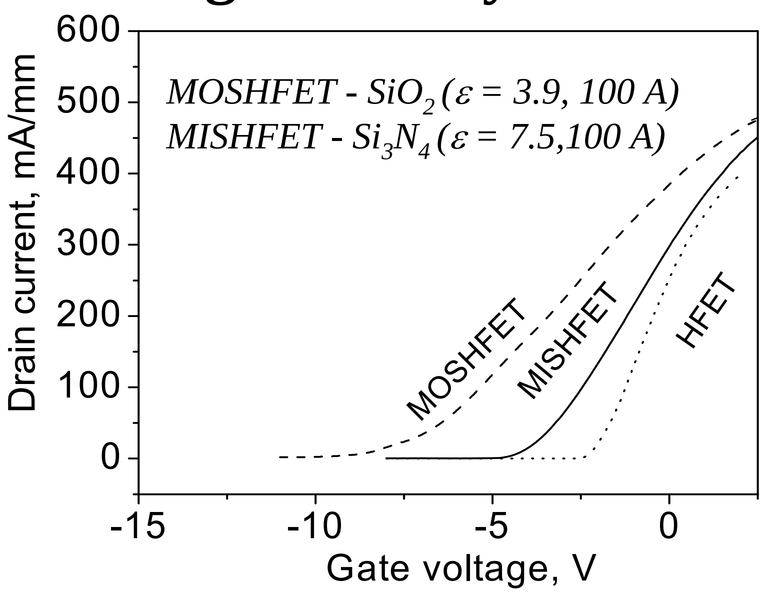
From "AlGaN-GaN metal–oxide–semiconductor heterostructure field-effect transistors on SiC substrates" M. Asif Khan, X. Hu, A. Tarakji,G. Simin, and J. Yang, R. Gaska and M. S. Shur, APL 2000

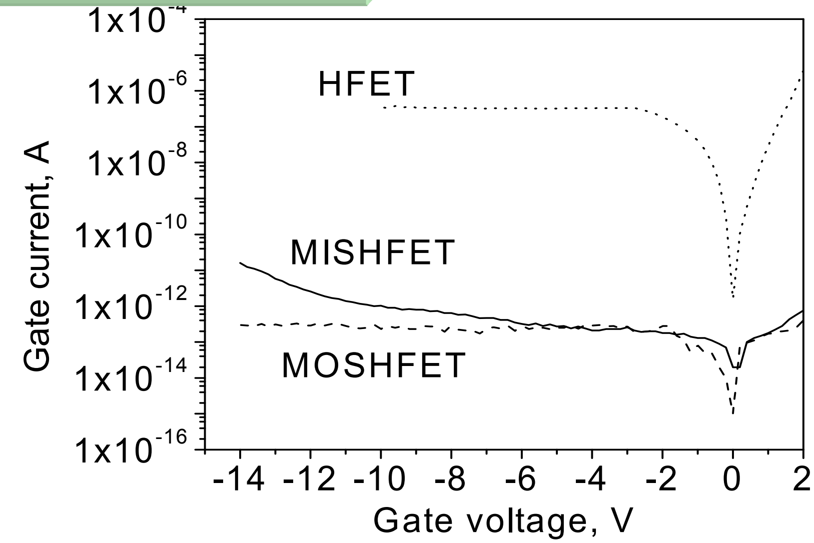
HFET, MOSHFET, and MISHFET



Currents up to 2.5 A/mm Demonstrated

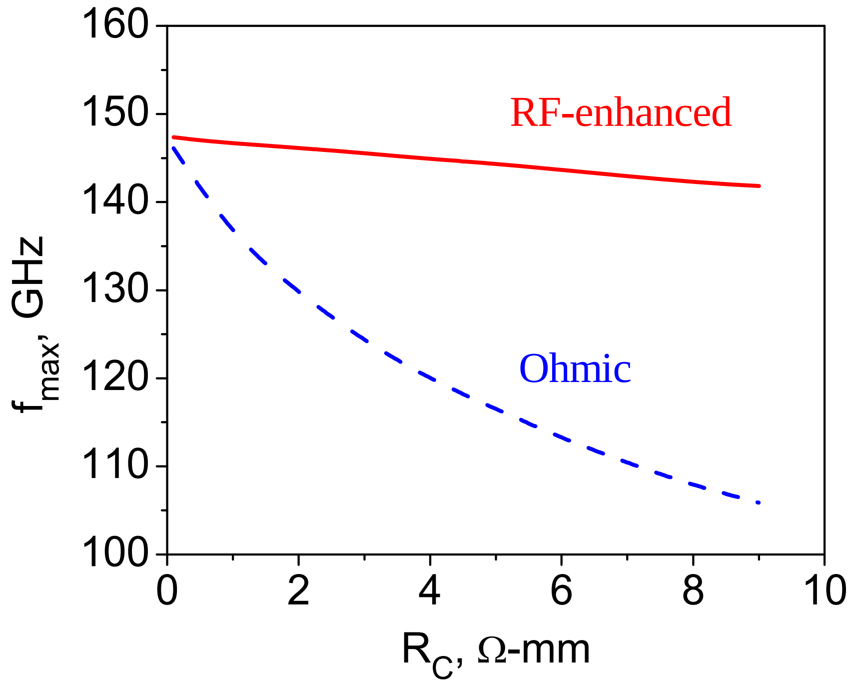
Leakage down by 10^6

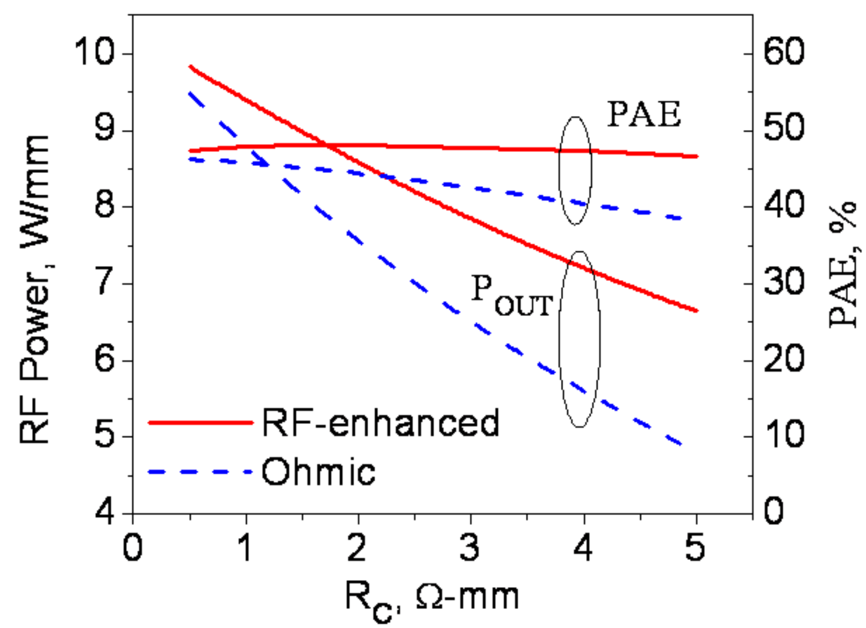




X. Hu, A. Koudymov, G. Simin, J. Yang, M. Asif Khan, A. Tarakji, M. S. Shur and R. Gaska Appl. Phys. Lett, v.79, p.2832-2834 (2001)

MOSHFET with RF-enhanced Contacts: f_{max}, Power, PAE



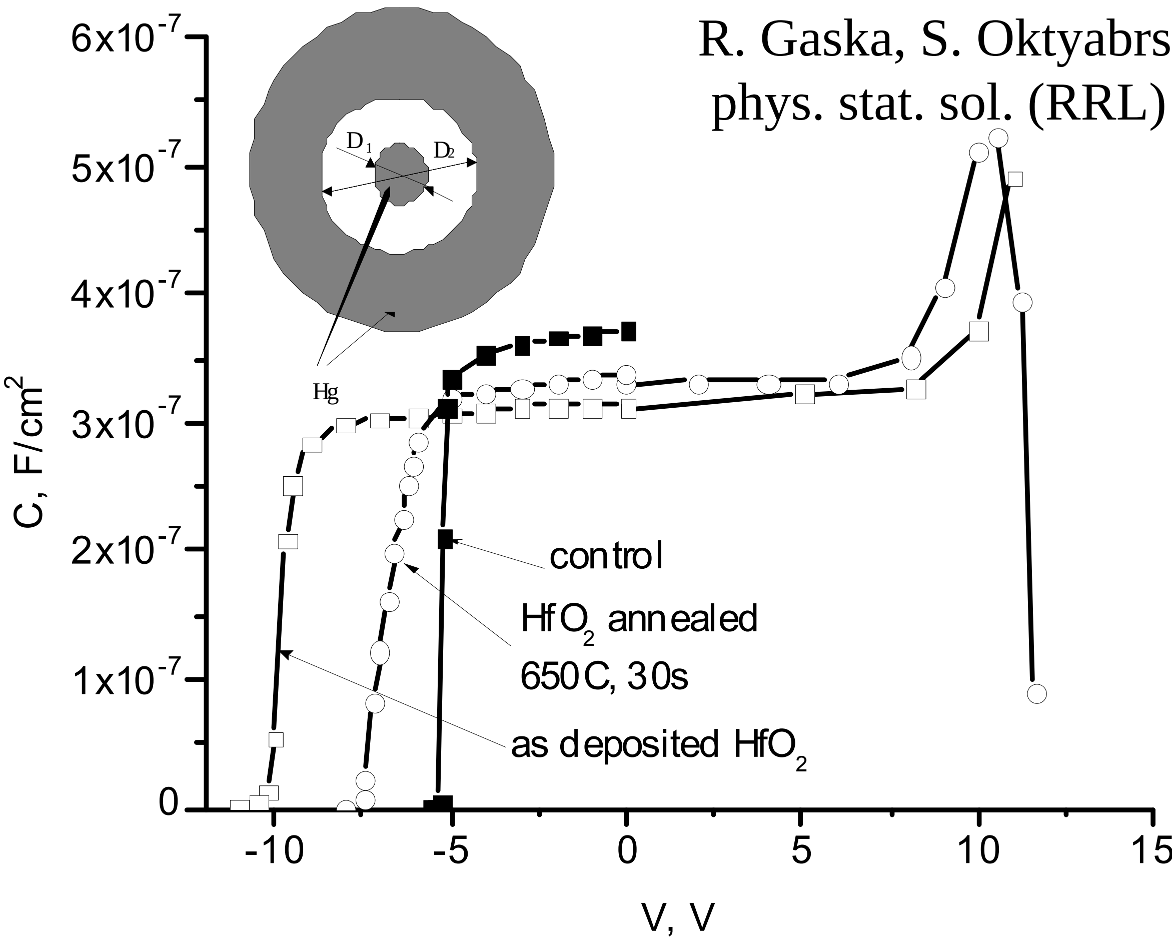


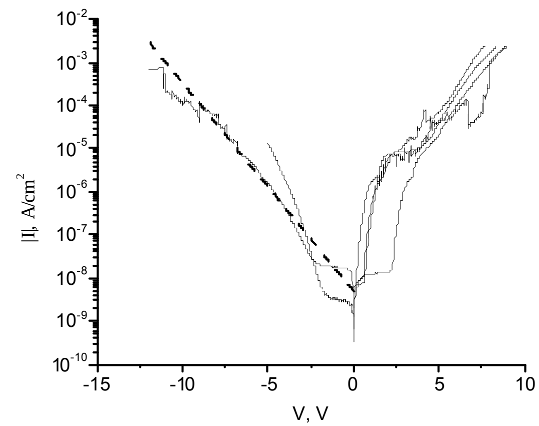
From: G. Simin and Z-J. Yang, RF-Enhanced Contacts to Wide Bandgap Devices, IEEE EDL V. 28, pp.2 -4 (2007)

$L_G = 0.2\ \mu m$; $V_D = 30\ V$

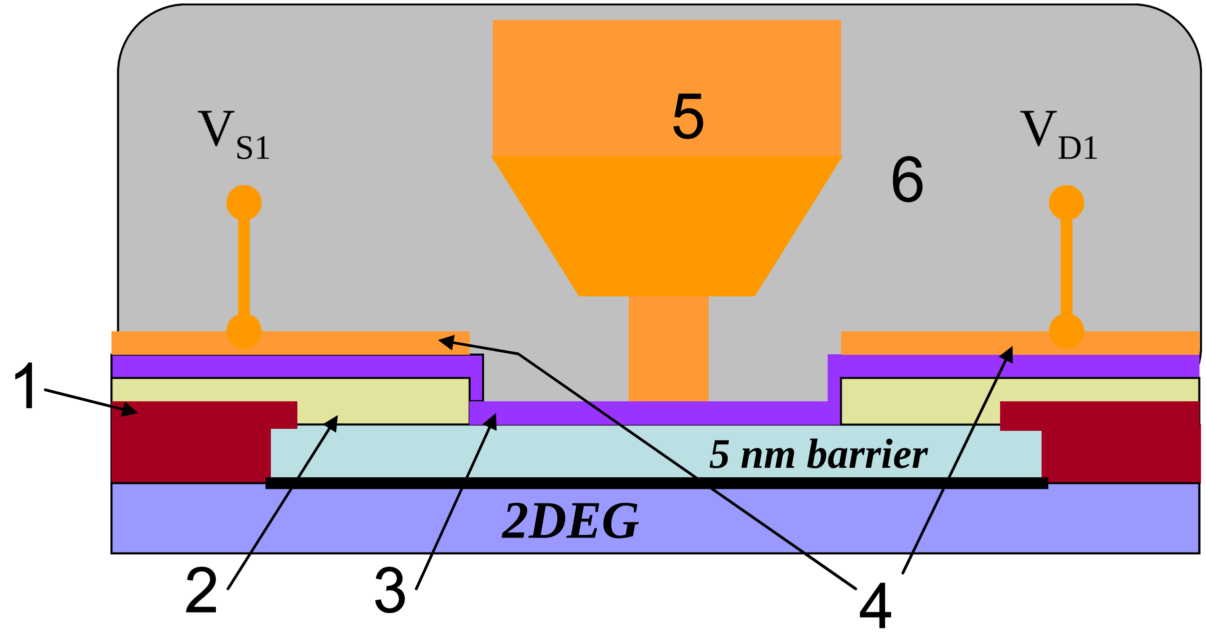
MISHFET with HfO_2

From V. Tokranov, S.L. Rumyantsev, M. S. Shur, R. Gaska, S. Oktyabrsky, R. Jain, N. Pala, phys. stat. sol. (RRL) **1**, No. 5, 199–201 (2007)





Novel THz Device design: 5-terminal THz GaN HFET



1 – Ohmic contact (low-T annealed);

2 – Field-control electrode isolation;

3 – Gate dielectric (HFO2)

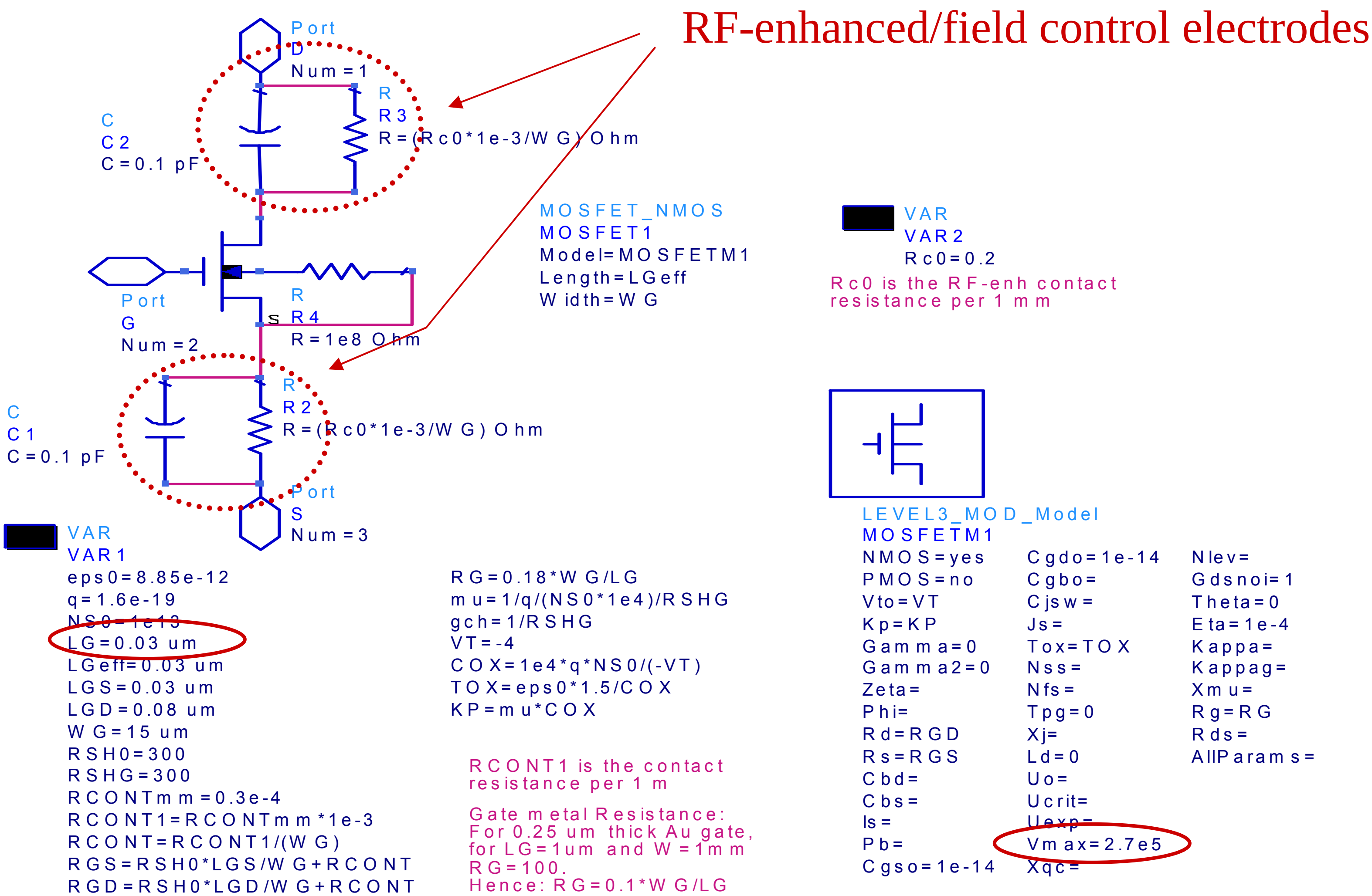
4 – Source and Drain field-control electrodes /RF-enhanced contacts;

5 – 30 nm Gate

6 – Flash-over suppressing encapsulation

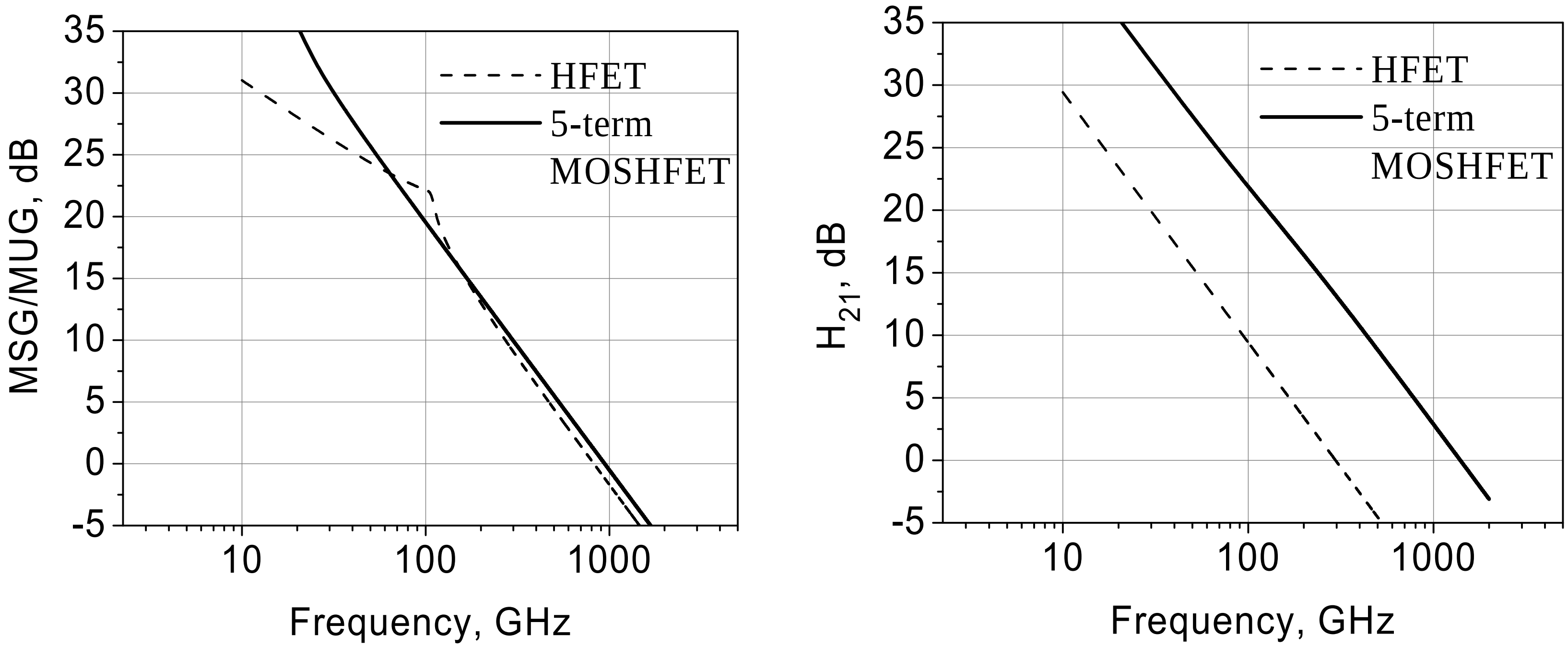
From G. Simin, M. Shur, and R. Gaska, presented at LEC-08, U of Delaware, 8/5/08

Device ADS model: “5-terminal” MOSHFET



From G. Simin, M. Shur, and R. Gaska, presented at LEC-08, U of Delaware, 8/5/08

Novel THz Device design:
5-terminal THz GaN HFET



Cut-off frequencies for regular (dash) and 5-terminal (solid) GaN HFETs with 30-nm long gate (ADS simulations).

From G. Simin, M. Shur, and R. Gaska, presented at LEC-08, U of Delaware, 8/5/08

Terahertz Radiation. Summary.

Technique	Power	Freq. Range (THz)	Tuning	Regime
Optically pumped THz lasers	> 100 mW	0.3 – 10	Discrete Lines	CW/Pulsed
Time Domain Spectroscopy	1 μW	0.1 - 2	No	Pulsed
Multipliers	μW - mW	0.1 - 1	10-15%	CW
Photomixing	μW	0.3 -10	Yes	CW

Free Electron Lasers kW power

THz Generation and Detection

Generation :

Free electron lasers
Quantum cascade lasers
Molecular lasers (CO_2 pump)
Femtosecond lasers
Photomixers
Back Wave Tube
Frequency multiplication (Gunn/IMPATT/Schottky)

HEMTs, HBTs - emerging
Plasma waves – emerging
Graphene THz lasers ?

Cryogenic detectors   NEP ~10^{-12} – 10^{-14} W/Hz$^{1/2}$

- Bolometers
- Photodetectors
- QWIPs
- Superconducting detectors (SIS, Josephson, bolometers)

Room temperature detectors NEP ~10^{-10} 10-12 W/Hz$^{1/2}$

- Pyroelectric detectors
- Golay cells
- Schottky diodes

References

- IMPATT, Gunn Oscillators:
  - –G. I. Haddad, J. R. East, and H. Eisele, International Journal of High Speed Electronics and Systems, vol. 13, pp. 395-427, 2003.
- Backward Wave Oscillators:
  - –MicroTech Instruments Inc., “Terahertz Spectrometers, Imaging Systems and Accessories”, Product catalog, Eugene OR, USA, 2007.
- Frequency Multipliers:
  - –T. W. Crowe, et al., "Terahertz sources and detectors," Orlando, FL, USA, 2005.
- Photomixers:
  - –S. Verghese, et al., Applied Physics Letters, vol. 71, pp. 2743-2745, 1997.
  - –M. Mikulics, et al., Applied Physics Letters, vol. 88, pp. 41118-1, 2006.
- Optically Pumped Laser:
  - –Coherent Inc., “SIFIR50, Stabilized Integrated FIR (THz) Laser System”, Datasheet, Santa Clara, CA, USA, 2007.
- Quantum Cascade Lasers:
  - –S. Barbieri, et al., Applied Physics Letters, vol. 85, pp. 1674-1676, 2004.
  - –R. Kohler, et al., Applied Physics Letters, vol. 82, pp. 1518-1520, 2003.

Tutorial Outline

- History
- Application examples
- Terahertz Photonics
- Terahertz Electronics
- **Plasma wave electronics**
- Terahertz properties of grainy multifunctional materials
- Conclusions and future work

THz chip Using Ballistic Transport

M. S. Shur and L. F. Eastman (1979)

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-26, NO. 11, NOVEMBER 1979 1677

Ballistic Transport in Semiconductor at Low Temperatures for Low-Power High-Speed Logic

Ballistic Transistor Has Virtually Unimpeded Current Flow (Dec. 6, 1999)

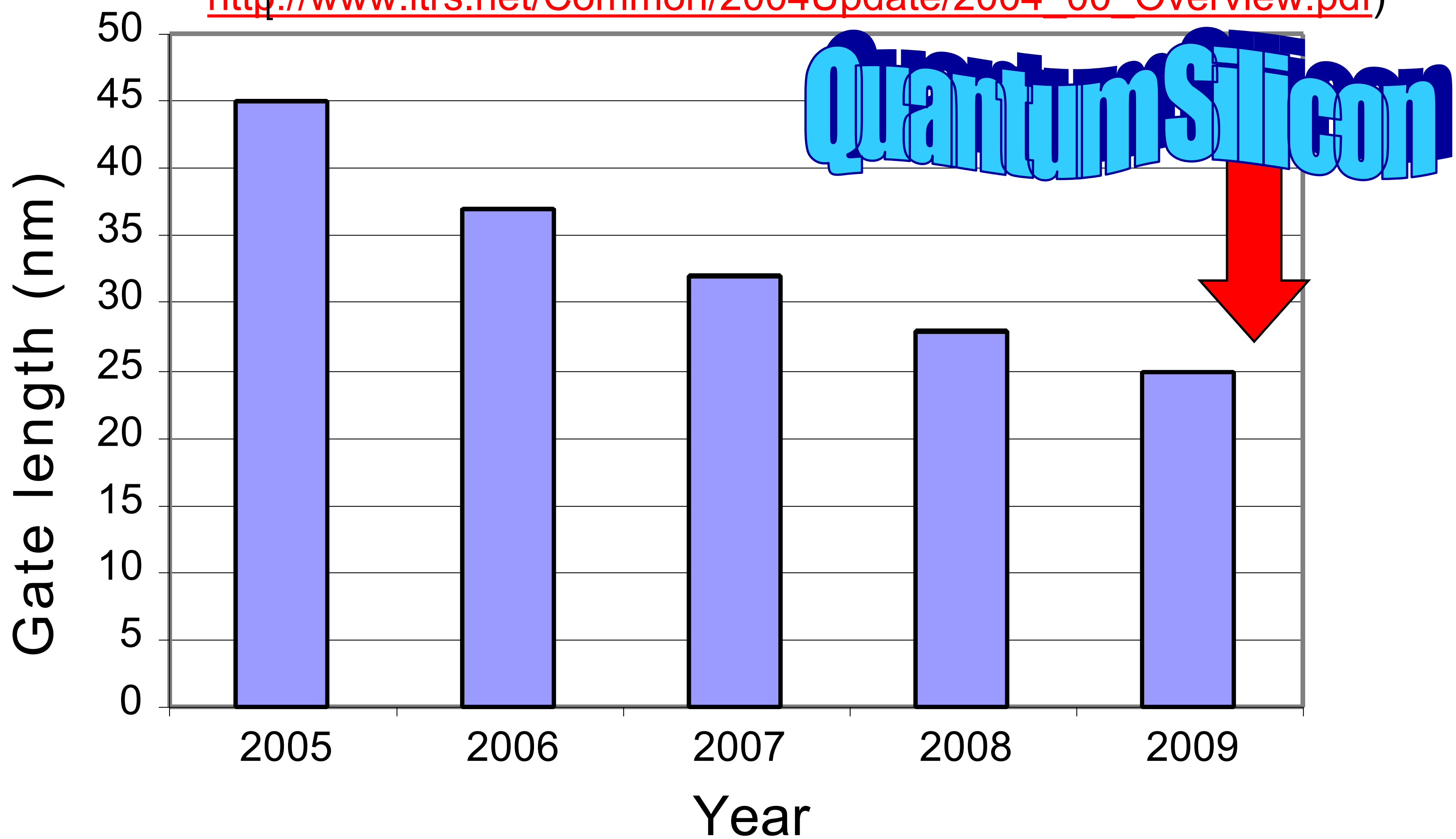
From http://www.bell-labs.com/news/1999/december/6/1.html

Intel plans Itanium 'leapfrog' to 32-nm
Colleen Taylor, Contributing Editor -- Electronic News, 6/14/2007

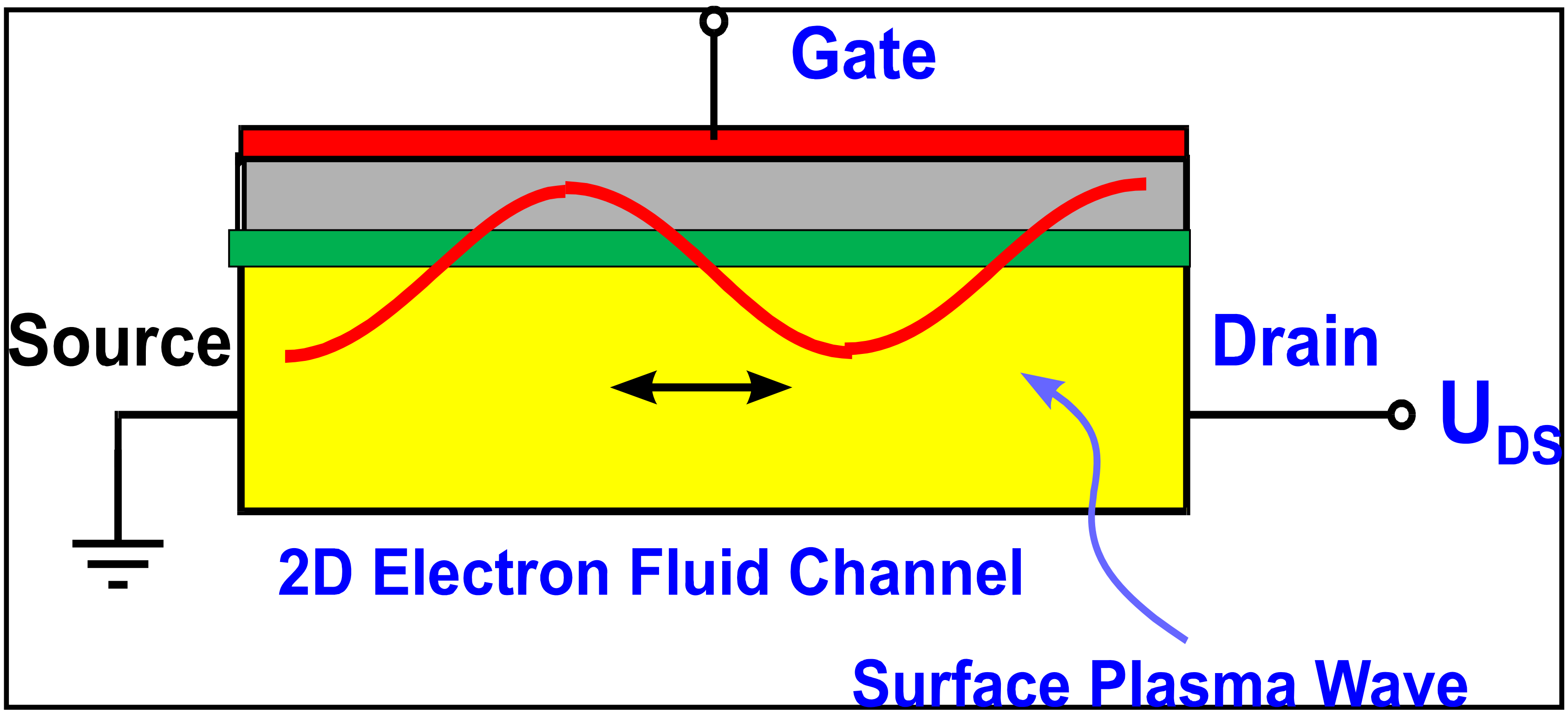
If the 25 nm node predicted by ITRS is reached in 2009, all transistors will be ballistic

All Transistors will be Ballistic in 2009

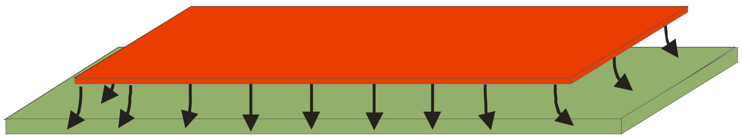
International Technology Roadmap for Semiconductors projections for minimum physical gate length. (Data from http://www.itrs.net/Common/2004Update/2004_00_Overview.pdf)



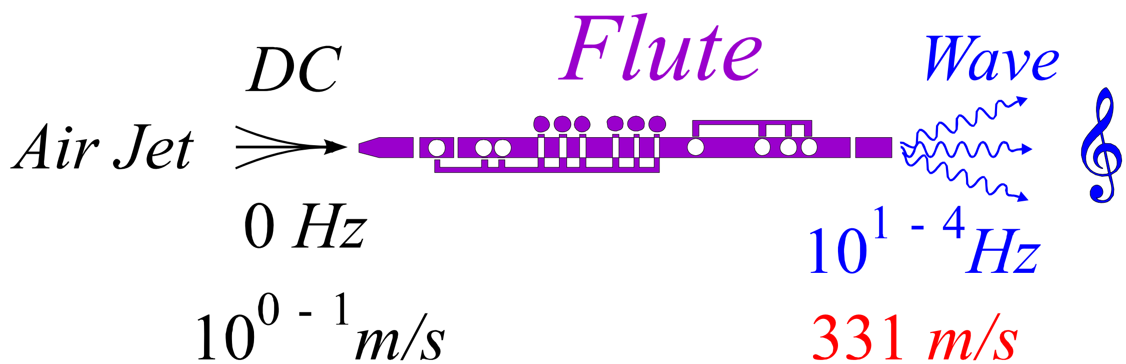
Waves of electron density (Plasma Waves)



THz Generation and Detection by 2D Plasma Waves



$$\omega = sk, \quad s = \sqrt{\frac{4\pi e^2 nd}{m\varepsilon}}, \qquad kd << 1$$



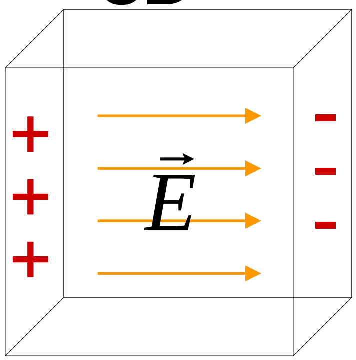
Instability: Dyakonov Shur PRL (1993)
Detection: Dyakonov Shur IEEE EDS (1996)

Plasma Wave Electronics

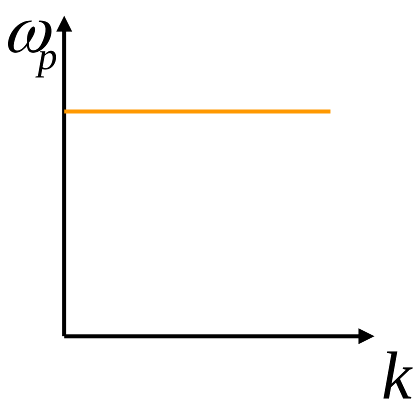
Hokusai Print

Dispersion of Plasma Waves

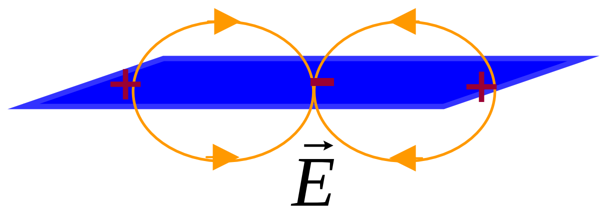
3D



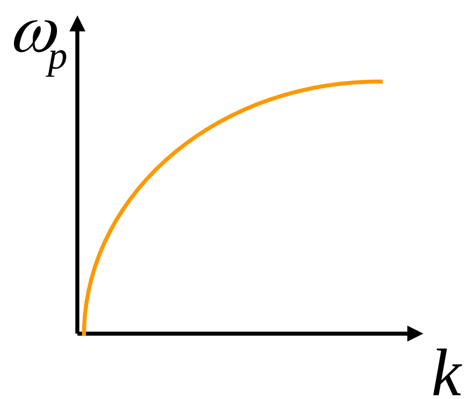
$$\omega_p = \sqrt{\frac{e^2 N_{3D}}{\varepsilon \varepsilon_0 m}}$$



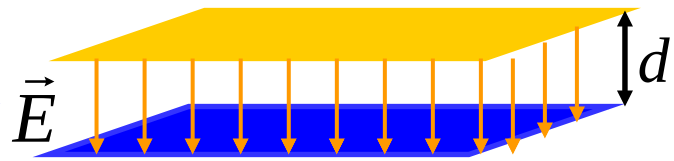
2D ungated



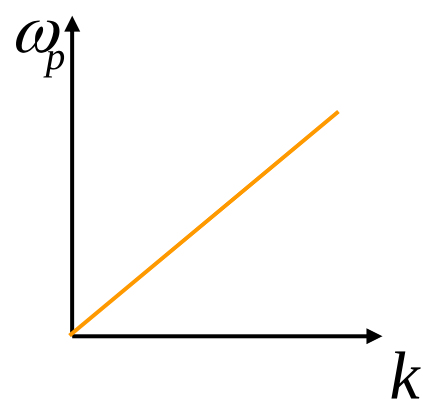
$$\omega_p = \sqrt{\frac{e^2 N_{2D}}{2 \varepsilon \varepsilon_0 m} k}$$



2D gated



$$\omega_p = \sqrt{\frac{e^2 N_{2D} d}{\varepsilon \varepsilon_0 m}} k \quad kd << 1$$



Plasma Wave Instability in Ballistic FET

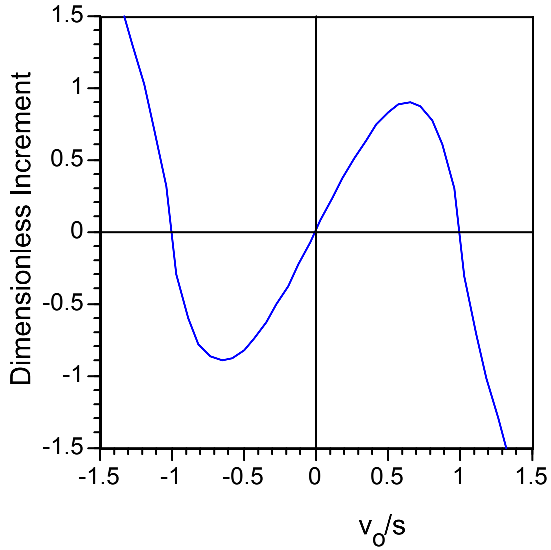
Boundary conditions

The source and drain are connected to a current source and the gate and source are connected to a voltage source, U_{gs}.
This corresponds to the constant value of $U = U_o$ at the source ($x = 0$) and to the constant value of the current at the drain ($x = L$).

$$\omega' = \frac{\left|s^2 - v_o^2\right|}{2Ls}\pi n \qquad \omega'' = \frac{s^2 - v_o^2}{2Ls}\ln\left|\frac{s+v_o}{s-v_o}\right|$$

$$s = (eU_o/m)^{1/2}$$

where n is an odd integer for $|v_o| < s$ and an even integer for $|v_o| > s$.

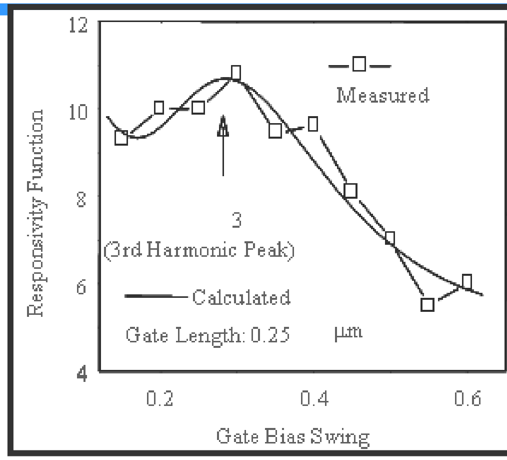


Demonstrated Plasma Wave Phenomena

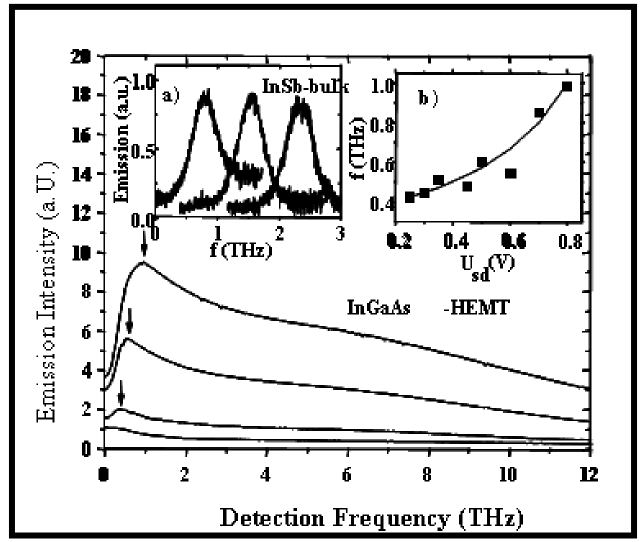
- Resonant detector

J. Lu and M. Shur (1998)

W. Knap et al (2002)



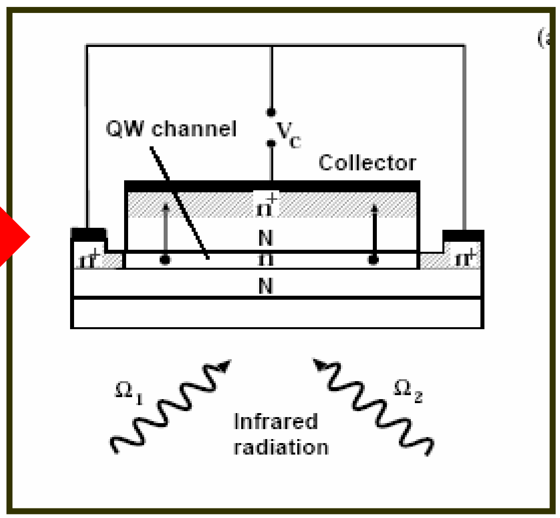
- Emission



Deng et al (2004)
W. Knap et al (2004)

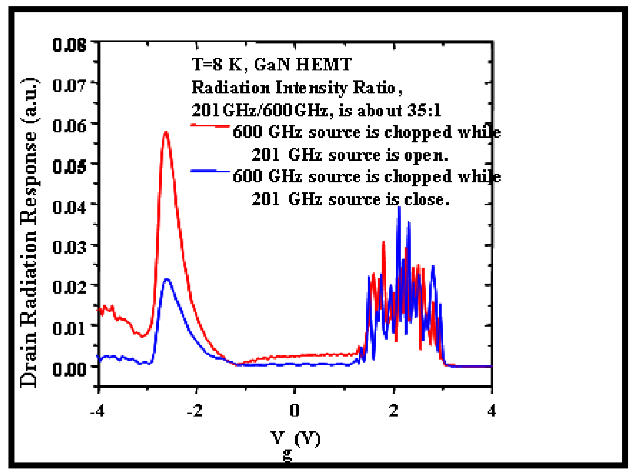
- Photomixer

V. Ryzhii et al (2002)
Otsuji et al (2003)



- Mixer

M. Lee et al (2005)



Plasma Electronics Advantages

- Small size (easy to fabricate matrixes/arrays)

- Compatible with VLSI technology

- For detectors:
  - High sensitivity
  - Broad spectral range
  - Band selectivity and tunability
  - Fast temporal response

2D Plasmonic Devices for THz Applications

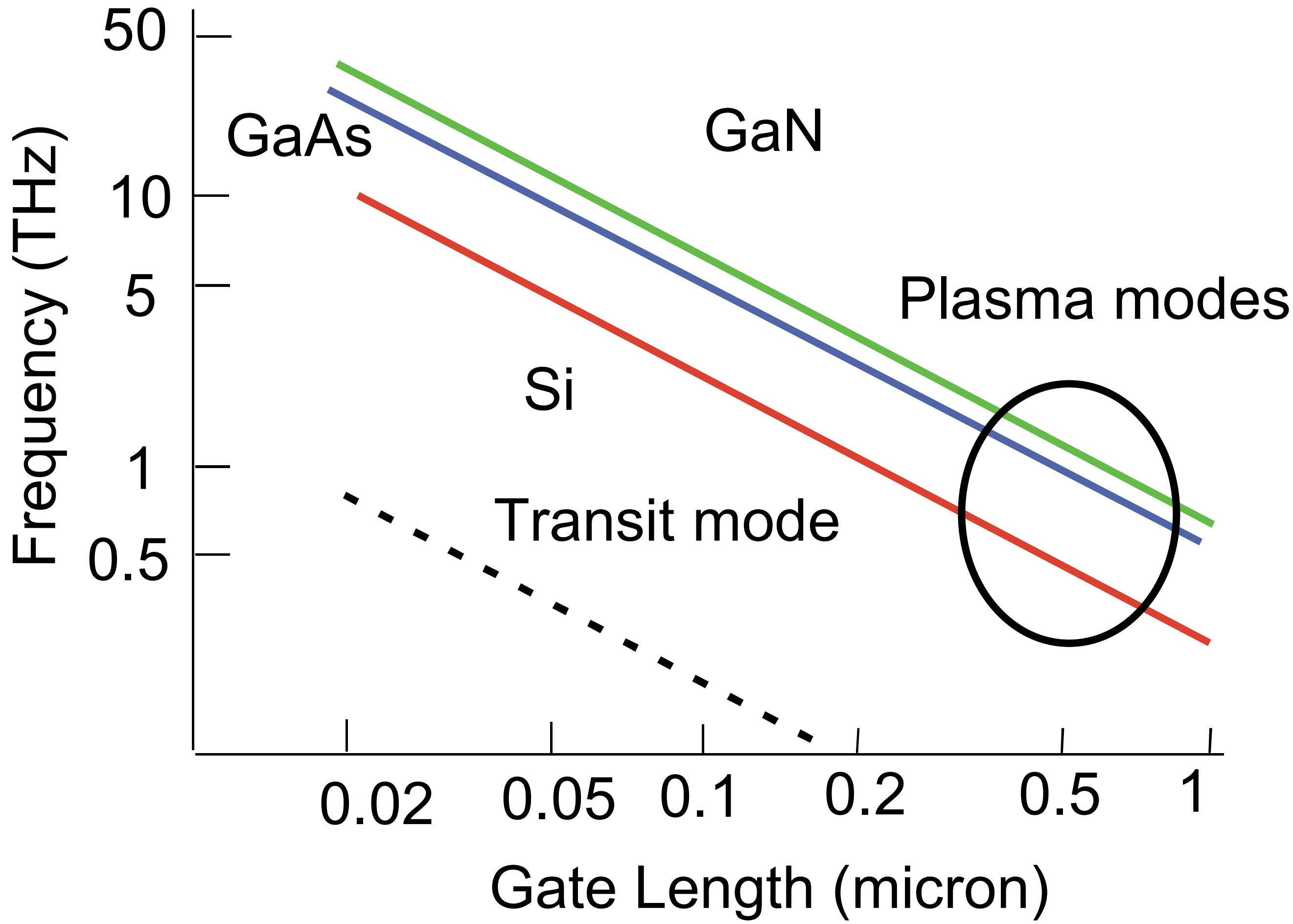
THz Detectors and Mixers

M. Dyakonov and M. Shur, IEEE T-ED (1996)
K. Guven et al., PRB (1997)
V. Ryzhii et al., JAP (2002)
W. Knap et al., APL, JAP (2002)
X.G. Peralta et al., APL (2002)
A. Satou et al., SST (2003)
V.V. Popov et al., JAP (2003)
V. Ryzhii et al., JAP (2003)
F. Teppe et al., APL (2005)
I.V. Kukushkin et al., APL (2005)
D. Veksler et al., PRB (2006)

THz Generators

M. Dyakonov, M. Shur, PRL (1993)
K. Hirakawa, APL (1995)
K. D. Maranowski, APL (1996)
V.V. Popov et al., Physica A (1997)
S.A. Mikhailov, PRB (1998); APL (1998)
P.Bakshi et al., APL (1999)
N. Sekine at al., APL (1999)
R. Bratshitsch et al., APL (2000)
Y. Deng at al., APL (2004)
W. Knap et al., APL (2004)
M. Dyakonov and M.S.Shur, APL (2005)
N. Dyakonova et al., APL (2006)
Otsuji APL (2006) DRC 2007

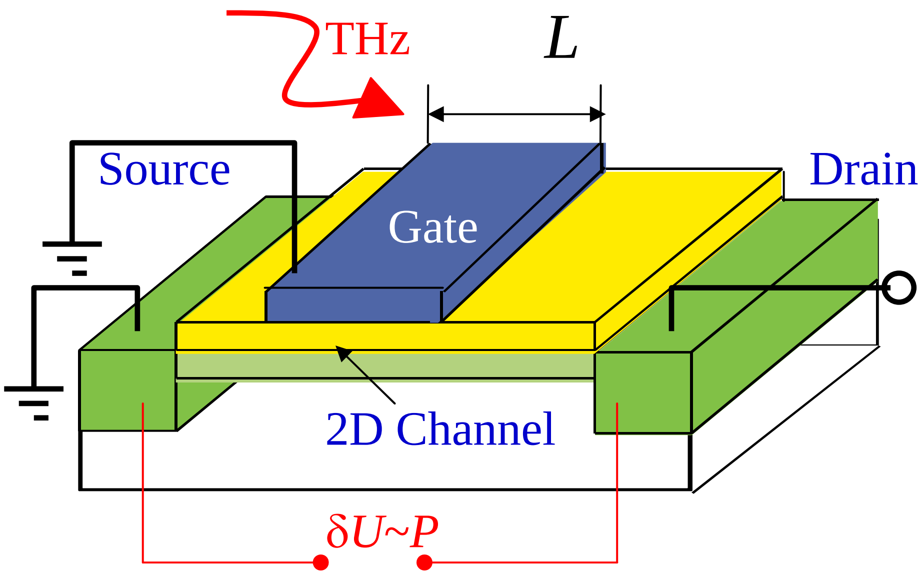
Semiconductors Competing for THz Applications



From V. Ryzhii and M.S. Shur, Plasma Wave Electronics Devices, ISDRS Digest, WP7-07-10, pp 200-201, Washington DC (2003)

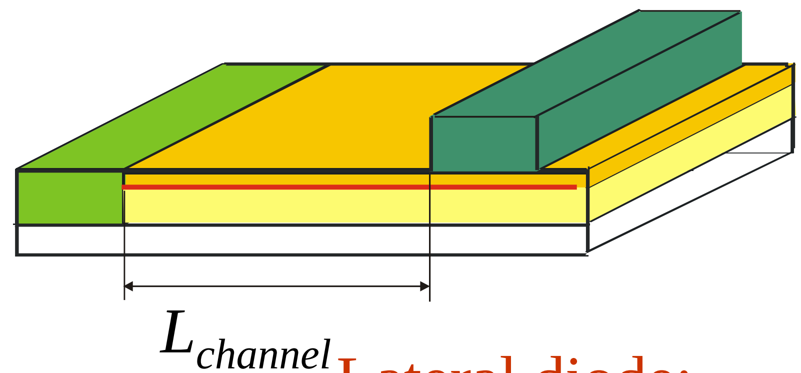
Channel with 2DEG as detection medium

FETs

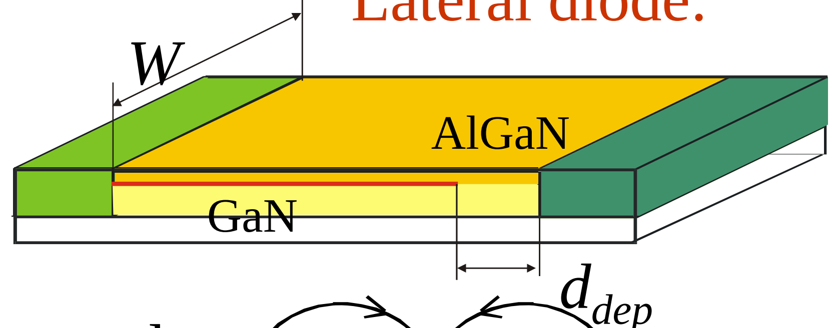


Diodes

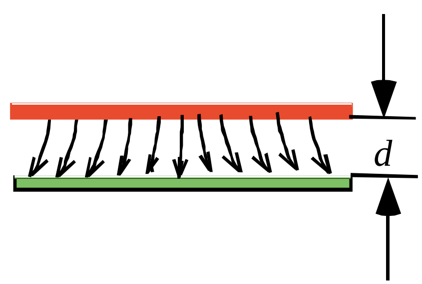
Vertical diode:



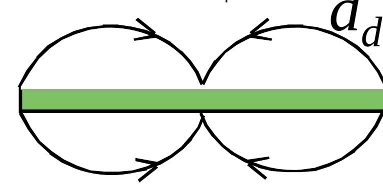
Lateral diode:



Gated
2D

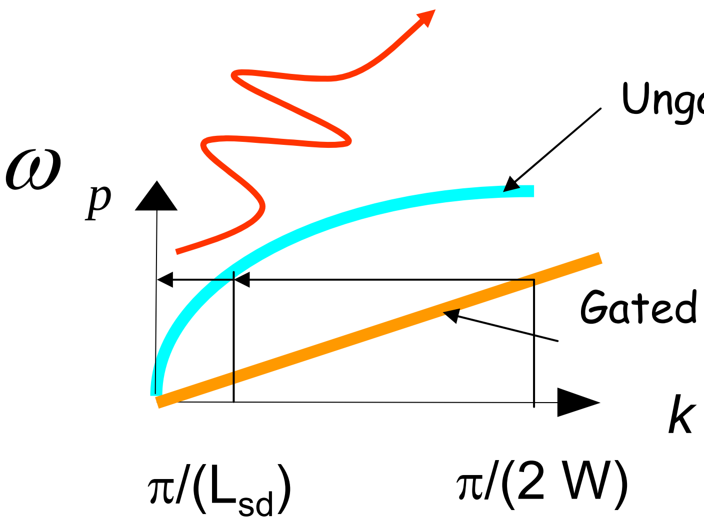


Ungated
2D

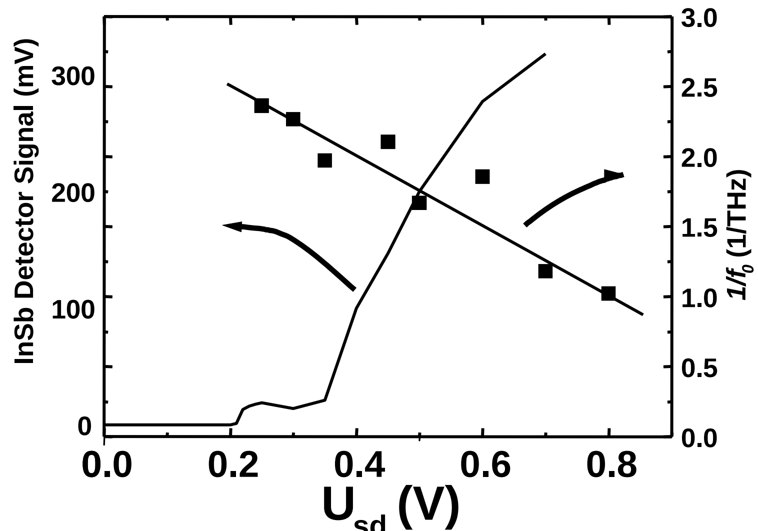


THz Generation in Nanometer-Gate HEMT via Gated-Ungated Plasmon Interaction

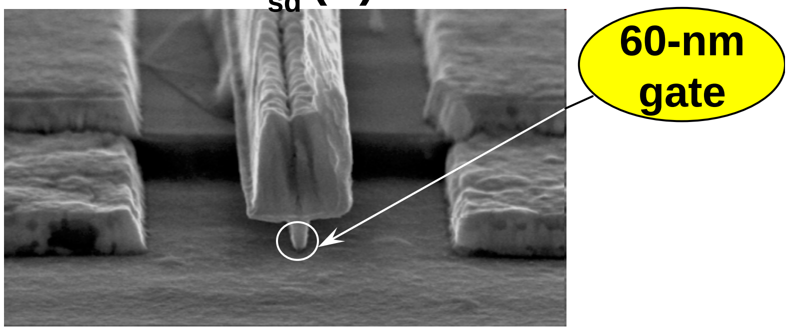
THz radiation



Knap W. et al, APL (2004)
IEEE Spectrum (May 2004)



The most efficient THz generation occurs when BOTH the ungated and gated plasmons are in resonance



InGaAs 60-nm-wide gate HEMT (Courtesy of W. Knap)

Achieved Detector Performance

GaAs :

1 THz detection demonstrated R ~ 10 - 10^3 V/W

n = 2×10^{11} cm^{-2} L = 0.2 μm.

Detection 120 GHz - 2.5 THz

GaN :

1 THz detection demonstrated

n = 2 $\times10^{13}$ cm^{-2} & L =2 μm

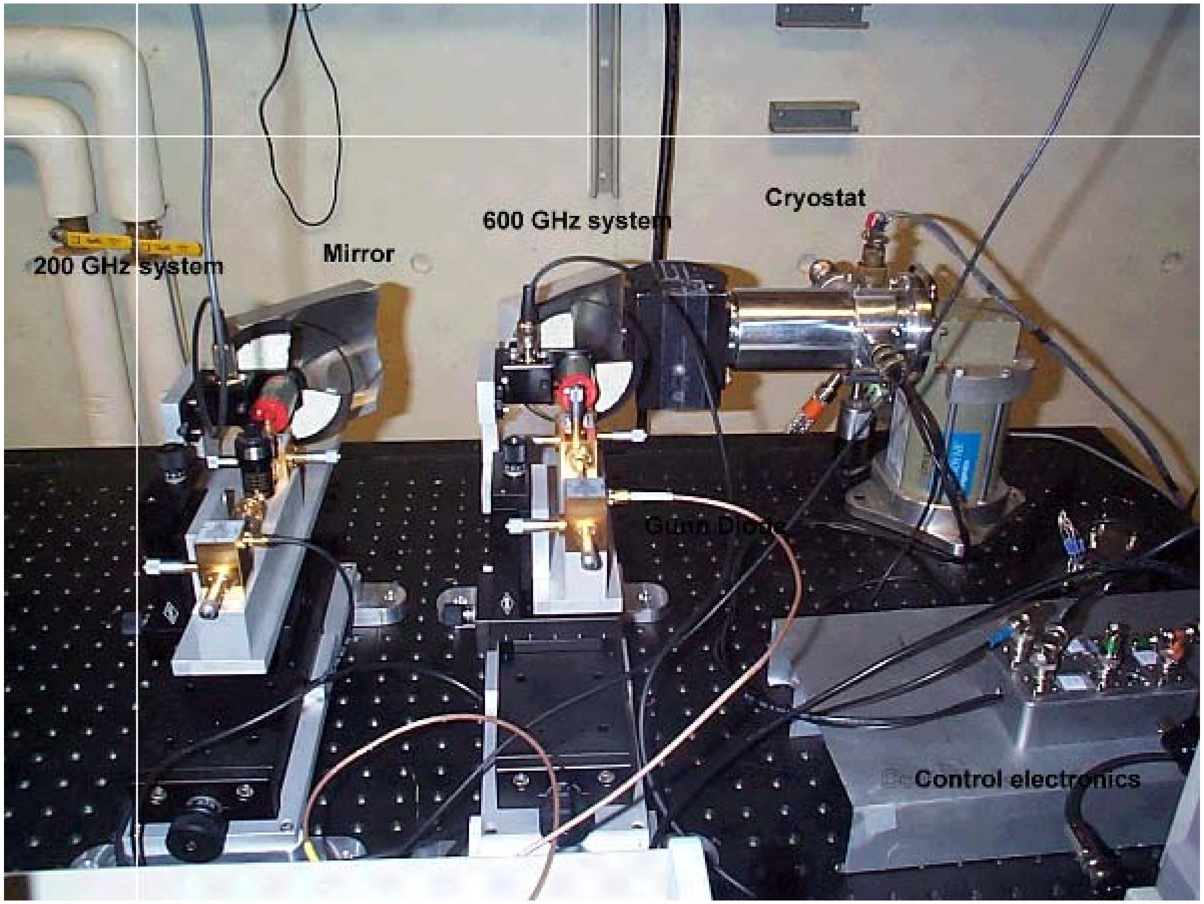
Room temperature generation

(Knap et al Veksler et al (2006)

Si : 120 GHz – 3 THz detection demonstrated

NEP ~ 10^{-10} W/Hz

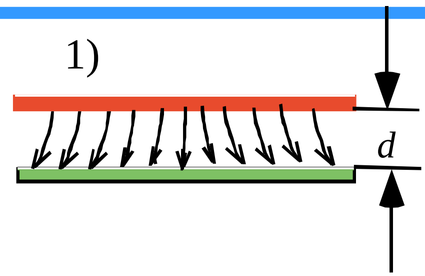
Experimental 200 and 600 GHz setups in our lab

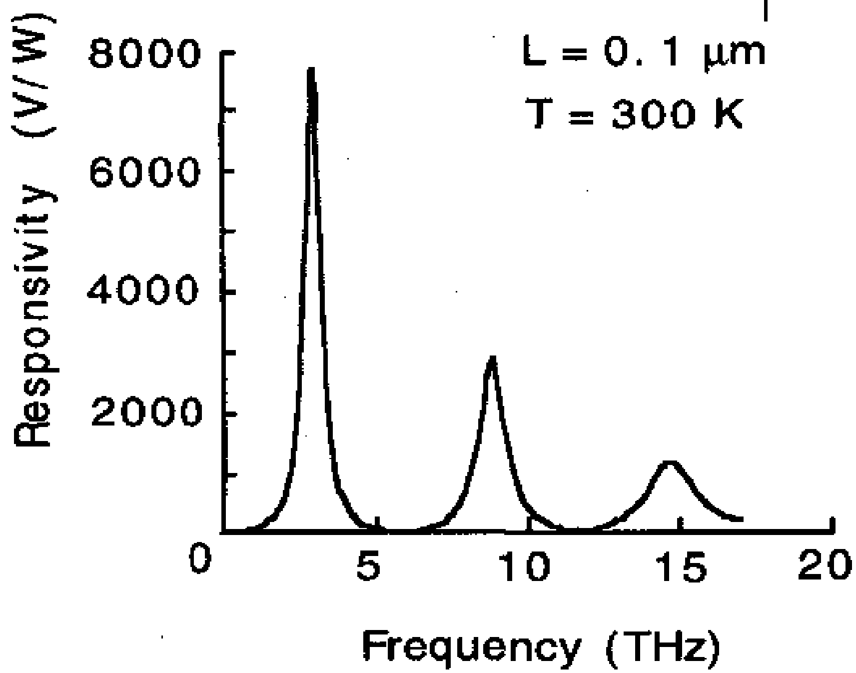


HEMT for Resonant THz detection

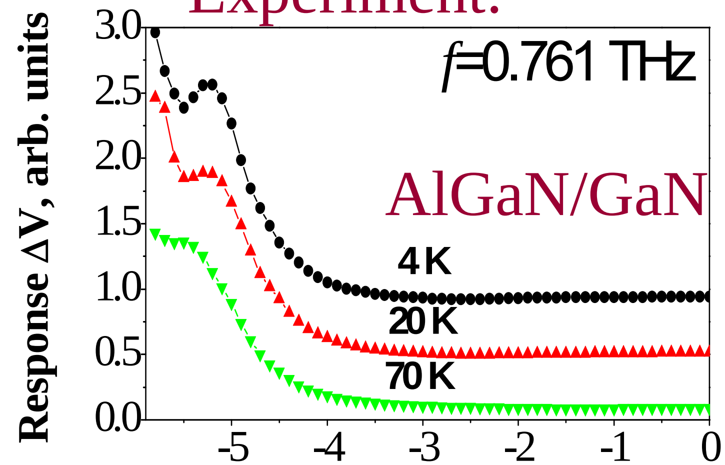
Theory:

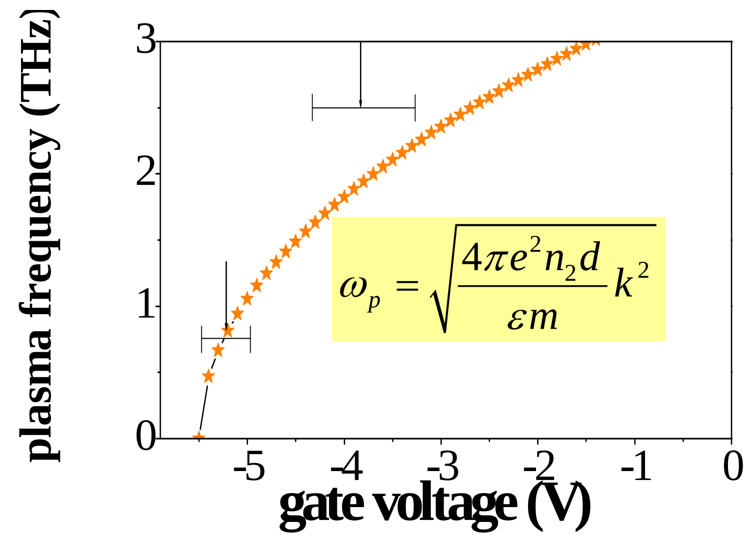
1)





Experiment: 2)





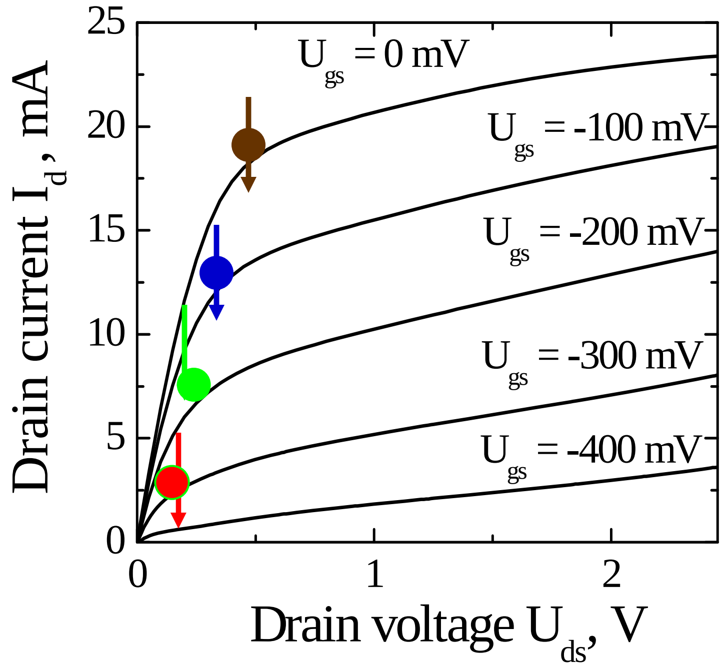
1) M. Dyakonov and M. S. Shur, *Phys. Rev. Lett.* ***71***, *2465 (1993)*

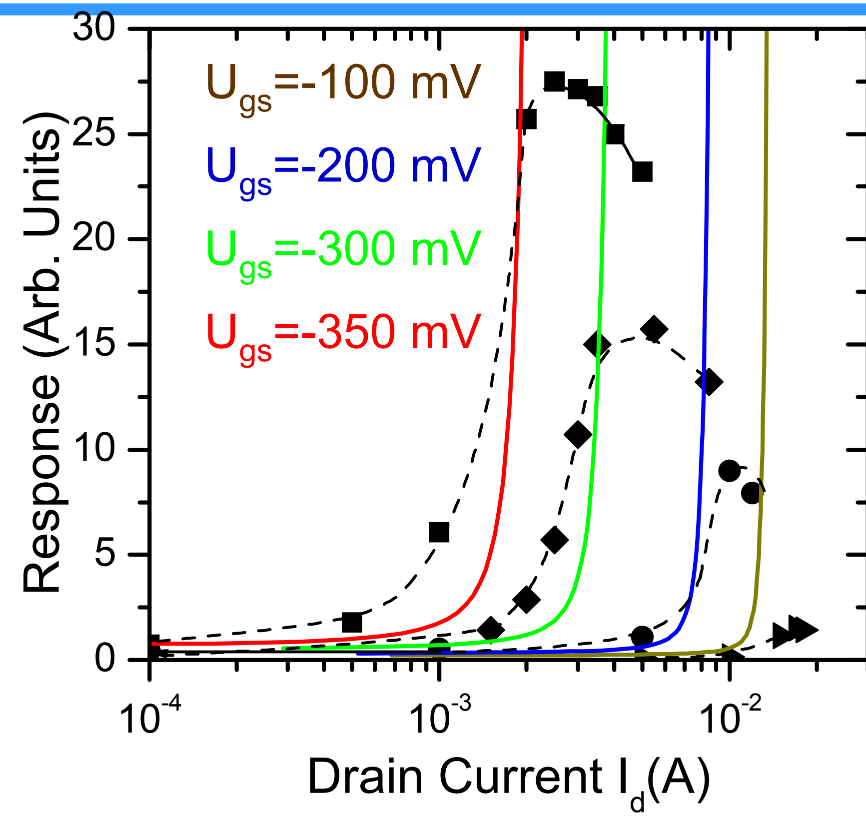
2) A. El Fatimy, N. Dyakonova, F. Teppe, W. Knap, N. Pala, R. Gaska, Q. Fareed, X. Hu, D. B. Veksler, S. Rumyantsev, M. S. Shur, D. Seliuta, G. Valusis, S. Bollaert, A. Shchepetov, Y. Roelens, C. Gaquiere, D. Theron, and A. Cappy, Electronics letters, Vol. 42 No. 23, 9 November (2006)

Non-resonant detection (ωτ<<1)

***f* = 0.2 THz; *T*=300 K**

250 nm GaAs FET





$$V_{response} = \frac{U_a^2}{4(U_{gs} - U_{th})(1 - j_d / j_{sat})^{1/2}}$$

$$j_d << j_{sat}$$

Symbols – experiment
Colored curves - theory

***D. Veksler** et al , Phys. Rev. B 73, 125328 (2006).*

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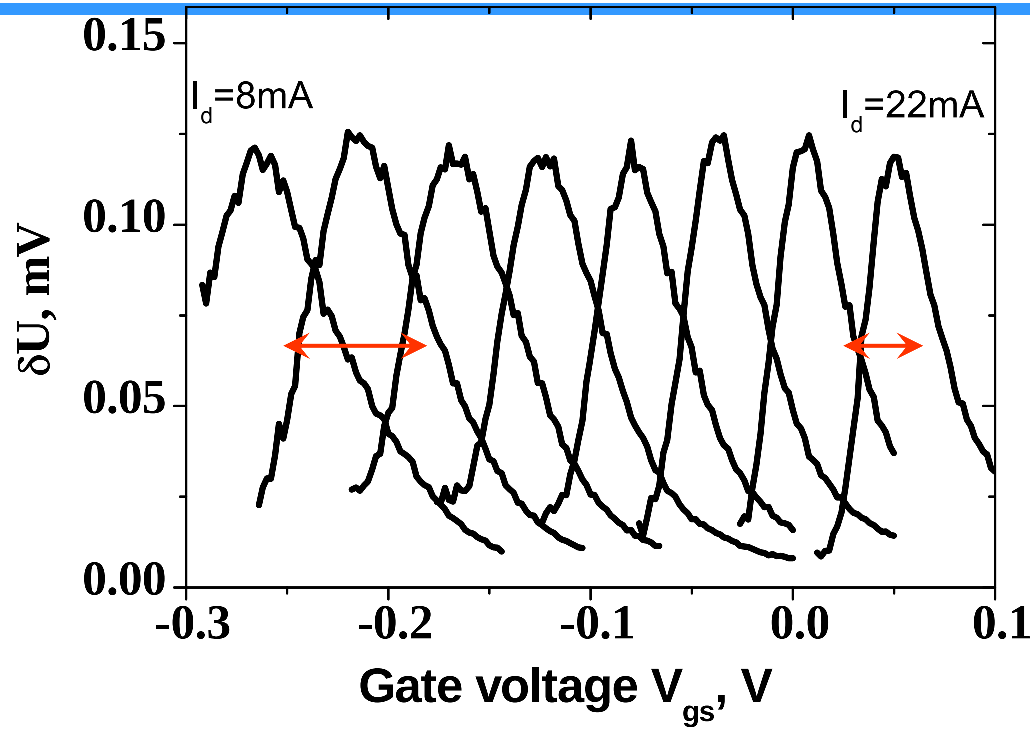
Resonant detection near instability threshold



f = 0.6 THz; T=300 K
GaAs FET 250 nm

$\omega_0 \tau < 1$, but $\omega_0 \tau_{eff} >> 1$

Instability increment

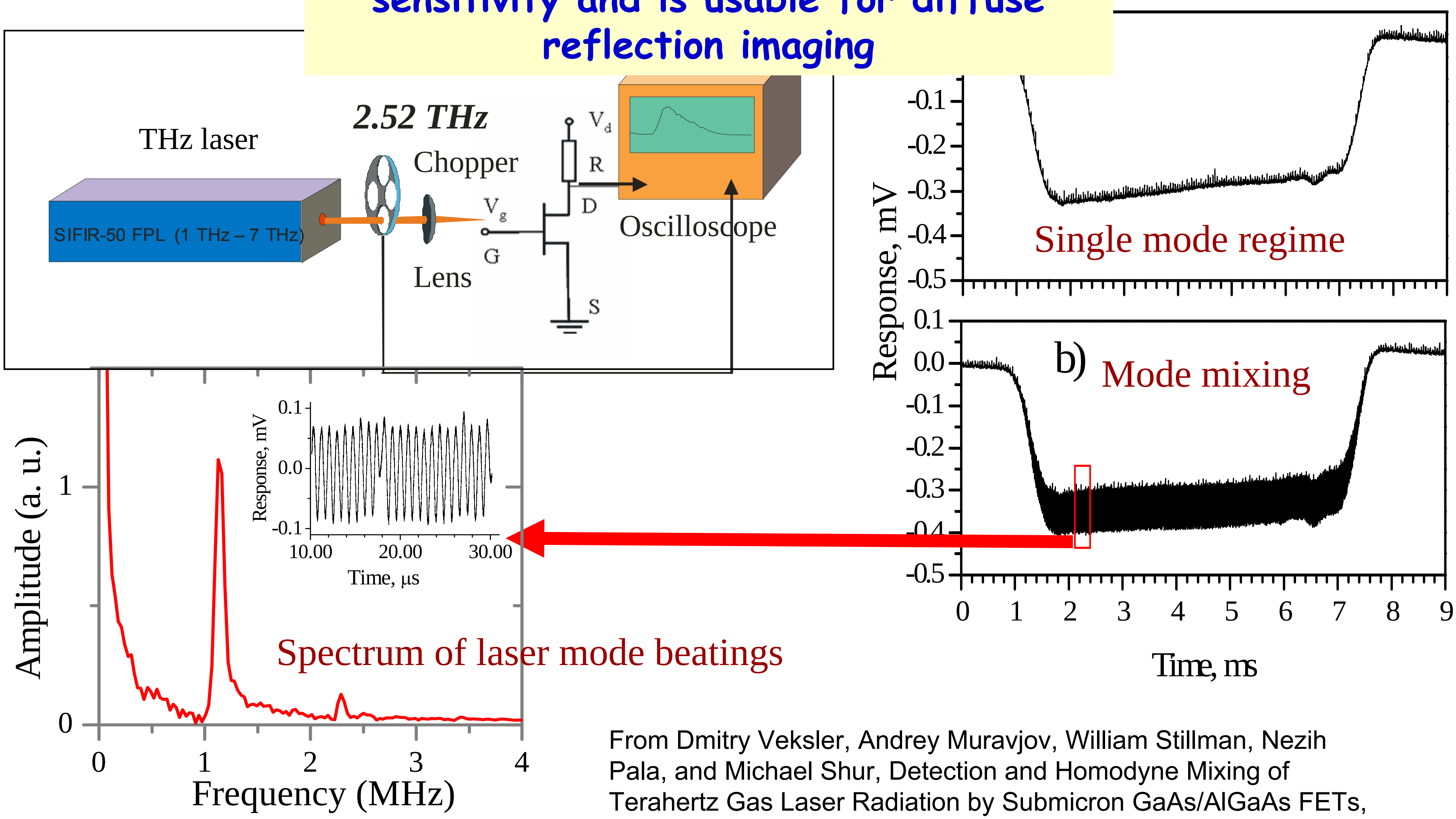
$$\frac{1}{2\tau_{eff}} = \left(\frac{1}{2\tau} - \frac{v_d}{L} \right)$$

The decrement decreases with electron velocity or drain current due to approaching to the threshold of the plasma wave instability.

F. Teppe, W. Knap, D. Veksler, et al, Appl. Phys. Lett. **87**, 052107 (2005)

Homodyne detection by plasma FET: Mixing of laser modes

Heterodyne detection has a much higher sensitivity and is usable for diffuse reflection imaging

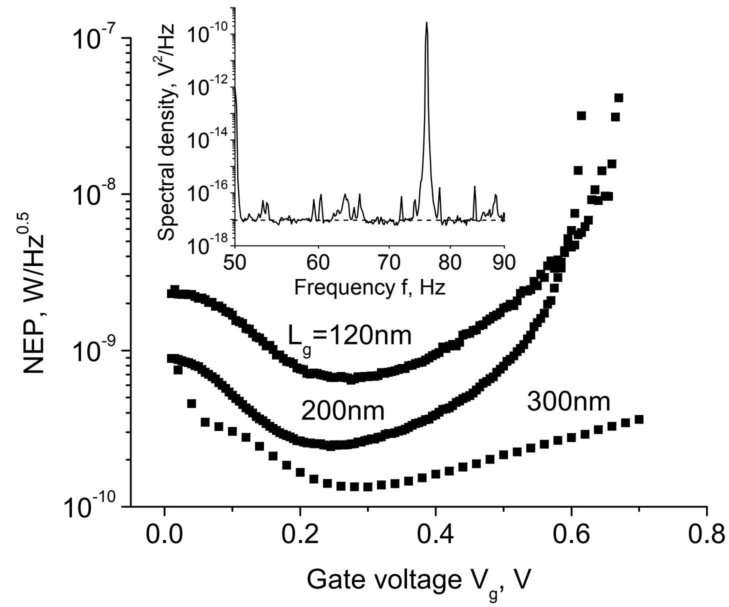


From Dmitry Veksler, Andrey Muravjov, William Stillman, Nezih Pala, and Michael Shur, Detection and Homodyne Mixing of Terahertz Gas Laser Radiation by Submicron GaAs/AlGaAs FETs, in Abstracts of IEEE sensors Conference, Atlanta, GA, October 2007

Comparison of THz Detection Devices (300 K)

Detector	NEP (W/Hz½)	Response time (Hz)
Microbolometer	Not tunable	
Pyroelectric	Not tunable	
Schottky Diode	Not tunable	
Plasma Wave Detector	Tunable	

Si MOS



Advantages of Plasma wave detector:

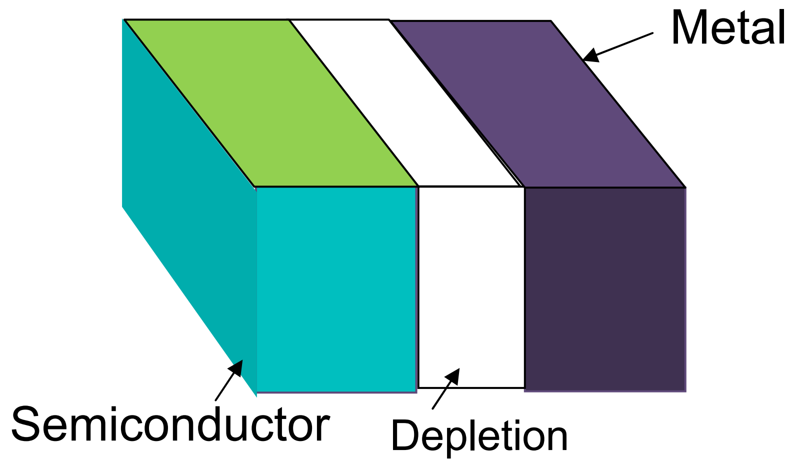
- Band selectivity and tunability (**resonant detection**)
- Fast temporal response
- Small size (easy to fabricate matrixes/arrays)
- Compatible with VLSI technology
- Broad spectral range

El Fatimy, N. Dyakonova, F. Teppe, W. Knap, ***D. B. Veksler****, S. Rumyantsev, M. S. Shur, N. Pala, R. Gaska, Q. Fareed, X. Hu, D. Seliuta, G. Valusis, C. Gaquiere, D. Theron, and A. Cappy, IElec. Lett. (2006).*

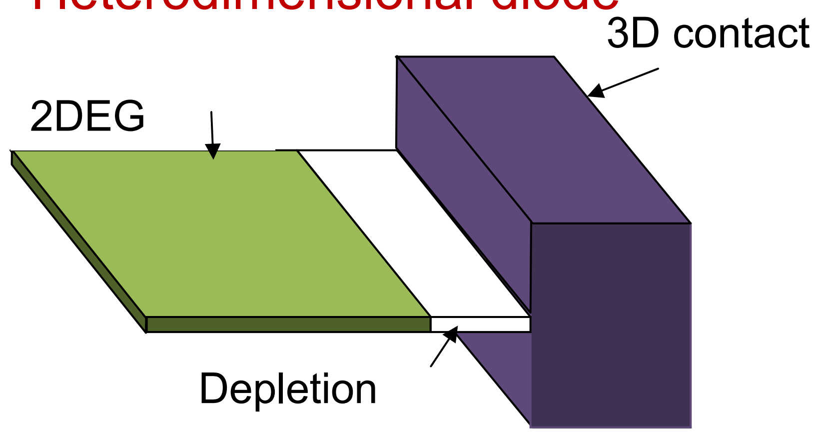
Table courtesy of D. Veksler, RPI

Schottky barrier (SB) + Plasma waves

Conventional diode



Heterodimensional diode



Heterodimensional diodes vs. conventional diodes

- Smaller series resistance
- Smaller capacitance

Hence, a higher operating frequency is expected

- 2d Plasma in series with the SB

W.C.B. Peatman, T.W. Crowe, and M. Shur, "A Novel Schottky/2-DEG Diode for Millimeter and Submillimeter Wave Multiplier Applications," IEEE Electron Device Lett., 13, 11 (1992)

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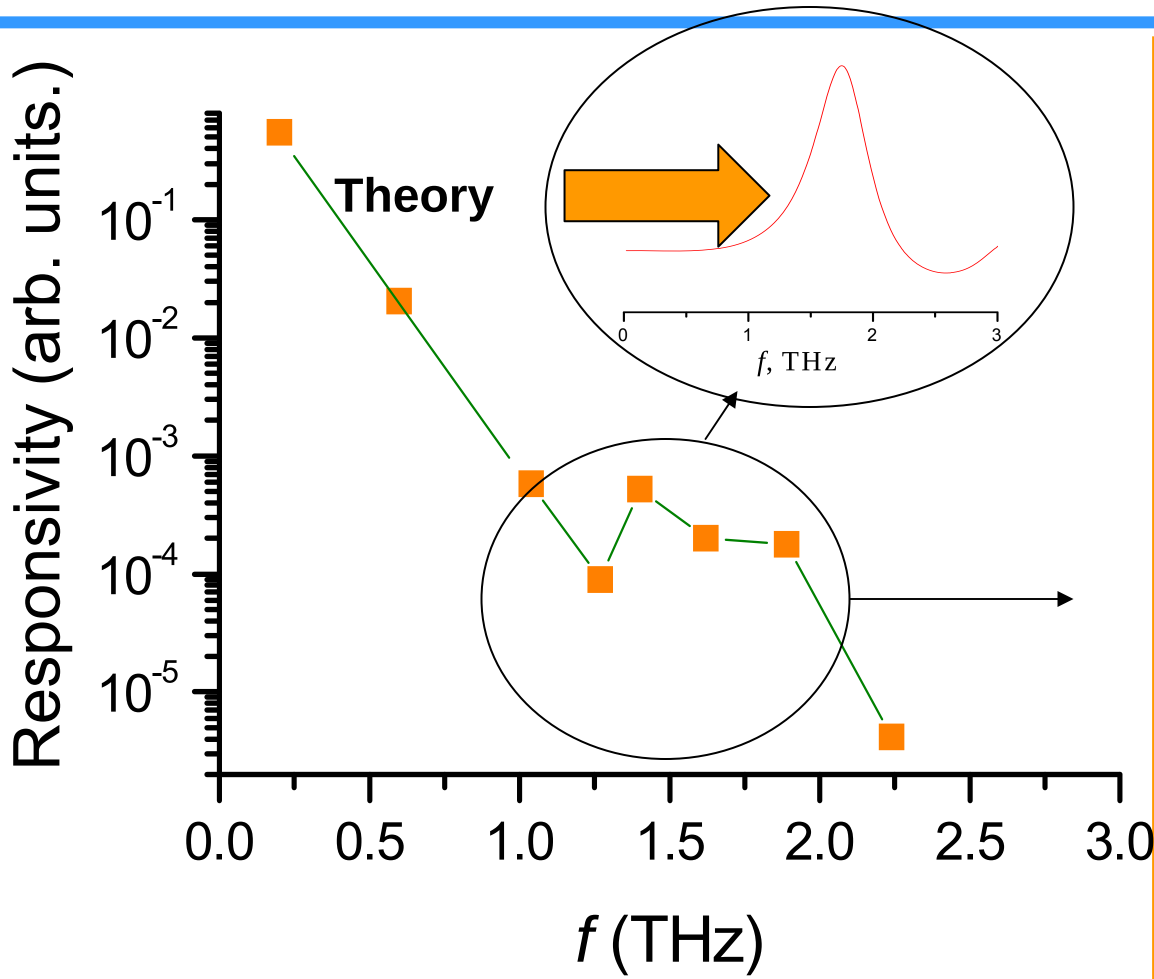
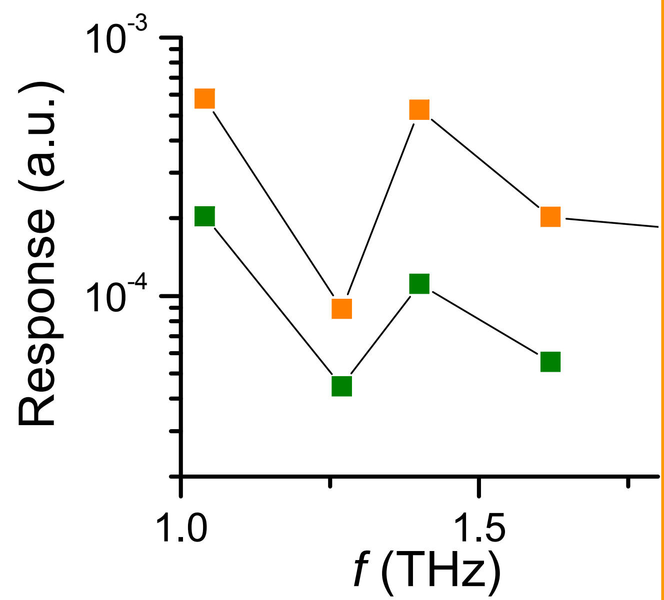
Responsivity vs. radiation frequency (zero bias)





D. Veksler, et al. Proc. 5th IEEE Conference on Sensors, p 323 (2006)

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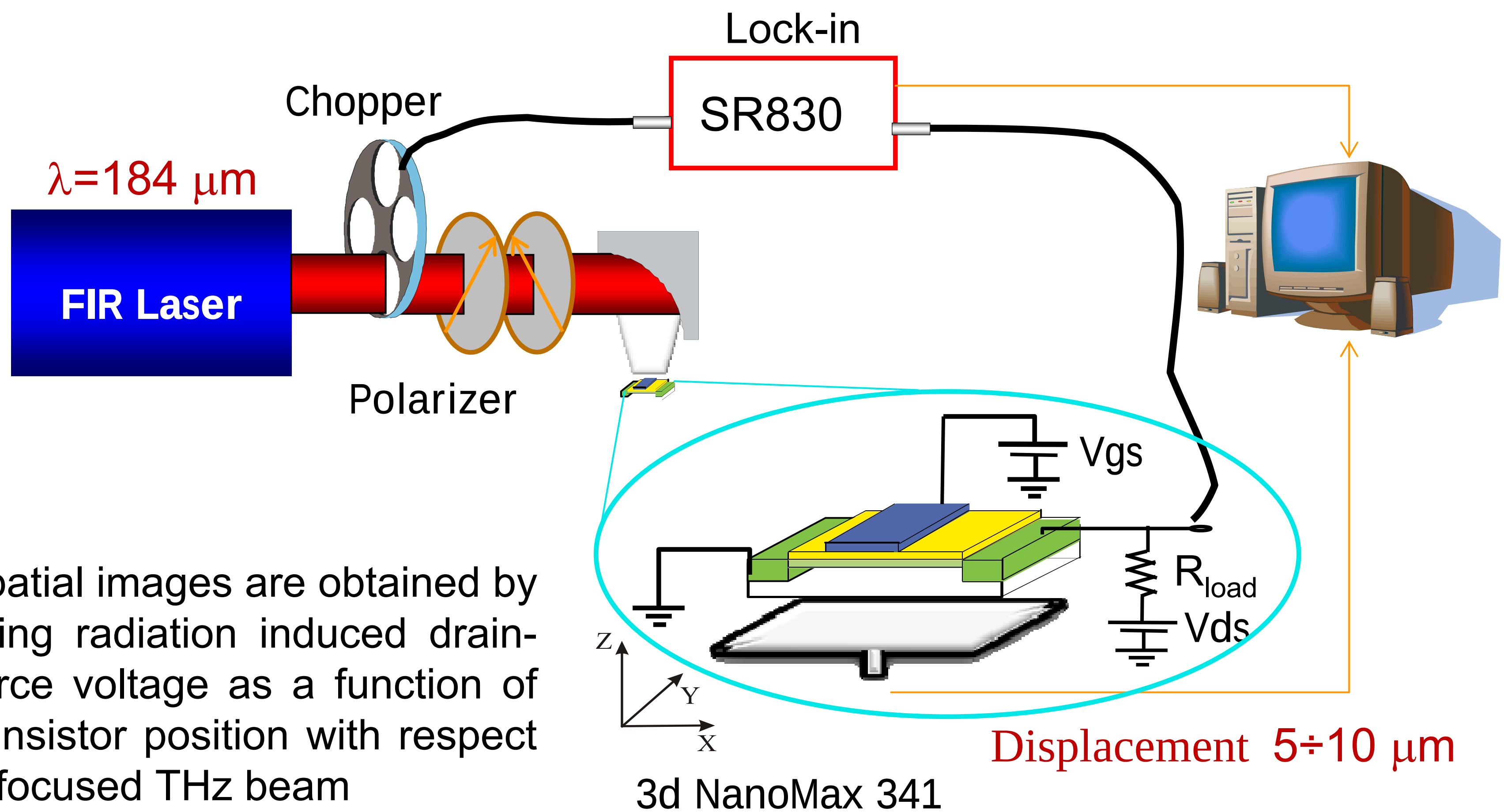
Coupling of THz radiation into transistor. Experiment



The spatial images are obtained by recording radiation induced drain-to-source voltage as a function of the transistor position with respect to the focused THz beam

Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

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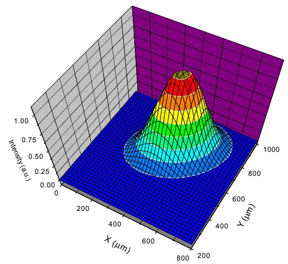
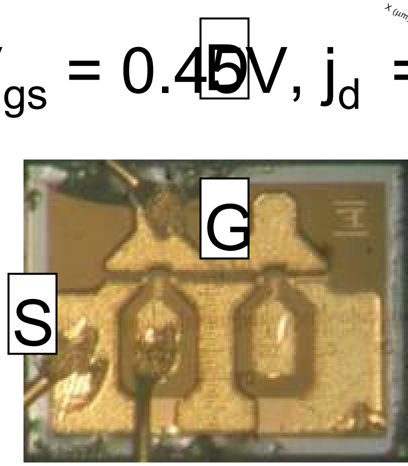
Transistor responsivity pattern exhibits two spots of maximum response with different signs

Beam profile in the focal spot:

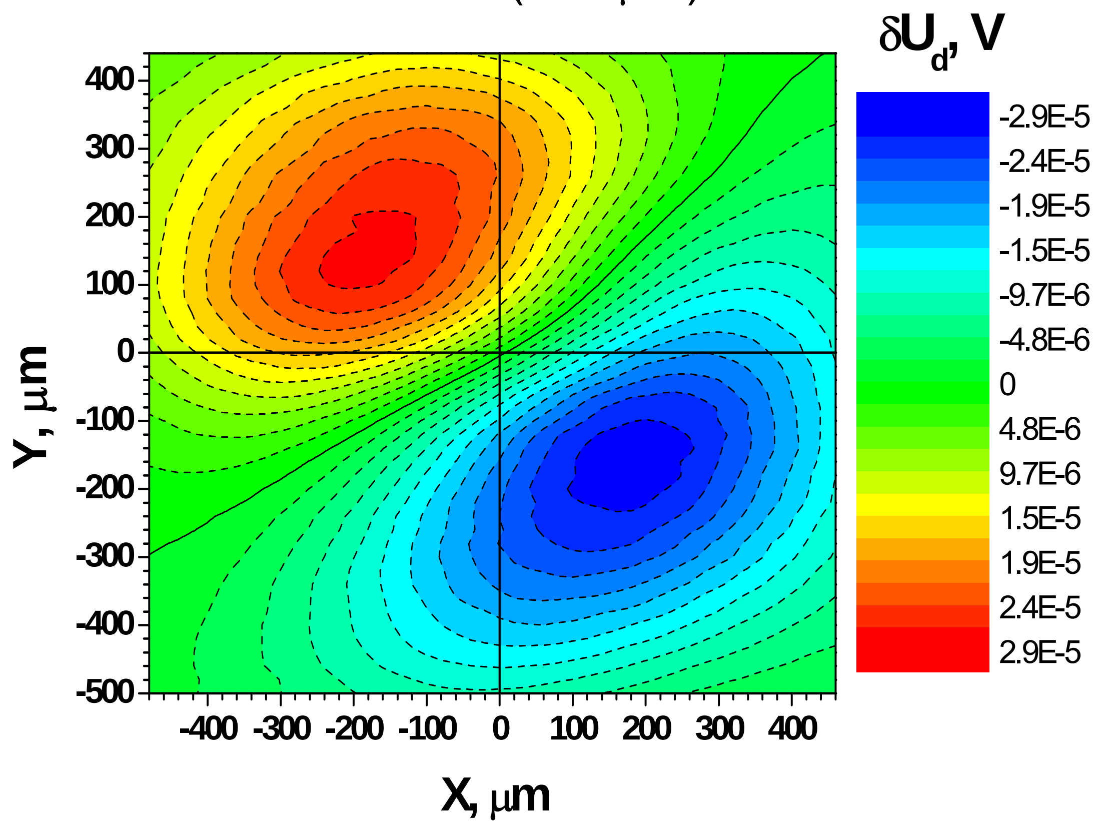


V_{gs} = 0.45V, j_d = 0



Fujitsu FHX06X
GaAs/AlGaAs HEMT
L_g=0.25μm
W=200μm

Source: Terahertz gas laser SIFIR-50 at 1.63 THz (184 μm)

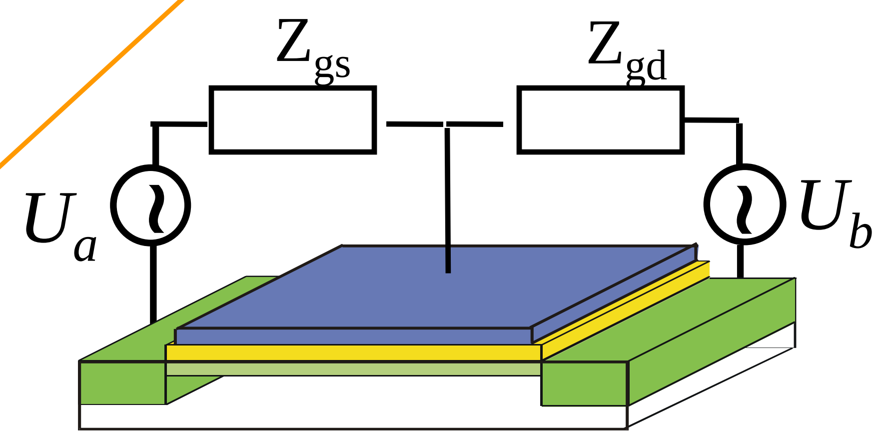


Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Theory

Hydrodynamic equations for 2D gas in the FET channel:

$$\begin{cases} \dfrac{\partial v}{\partial t} + v\dfrac{\partial v}{\partial x} + \dfrac{v}{\tau} + \dfrac{e}{m}\dfrac{\partial U}{\partial x} = 0 \\ \dfrac{\partial n}{\partial t} + \dfrac{\partial (nv)}{\partial x} = 0 \\ en = CU \end{cases}$$



Boundary conditions:

$$U_\omega(0) - j_\omega(0)Z = U_a, U_\omega(L) + j_\omega(L)Z = U_b.$$

We see that the response might have different signs depending on the ratio $|U_a|^2/|U_b|^2$

$$\omega_0 = \left(\mu U_g\right)^{-1/3}\left(CL^*\right)^{-2/3}$$

$$\delta V = -\frac{1}{4U_{gs} - U_{th}}\left(\frac{\omega_0}{\omega}\right)^3\left(\frac{|U_a|^2}{\left(1 - j_d/j_{sat}\right)^{1/2}} - \frac{|U_b|^2}{\left(1 - j_d/j_{sat}\right)^{3/2}}\right)$$

$$Z \approx -i\omega L^*$$

Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

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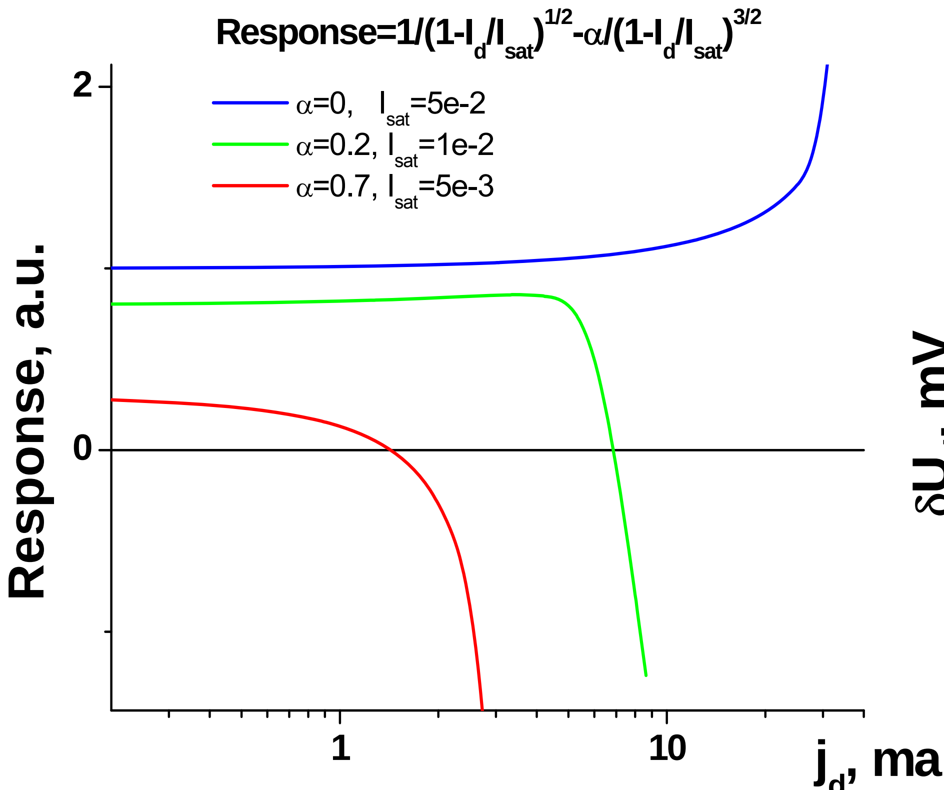
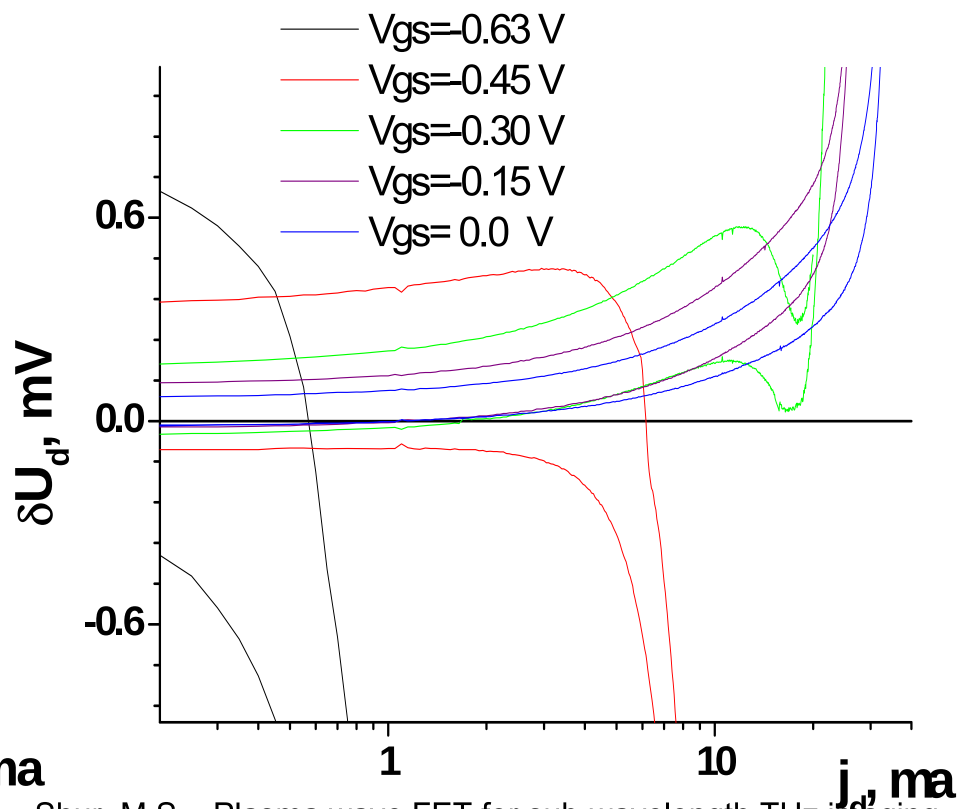
Transistor THz responsivity vs. drain current and gate voltage

Theory:

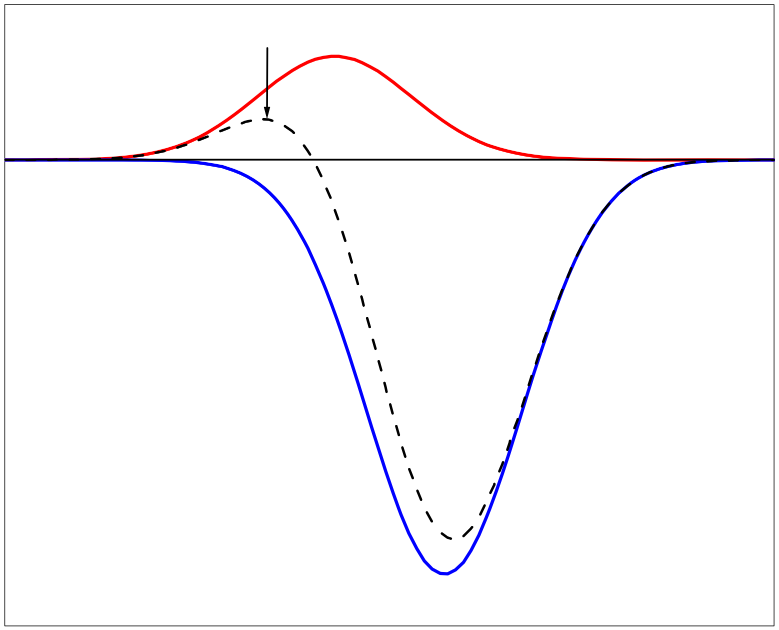
Experiment:





Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

THz Imaging with plasma FET



- THz image is a result of superposition of the responses from different parts of the transistor.
- Drain current leads to increase in the ratio between negative and positive responses. As a result the maximum of the response shifts in XY plane.

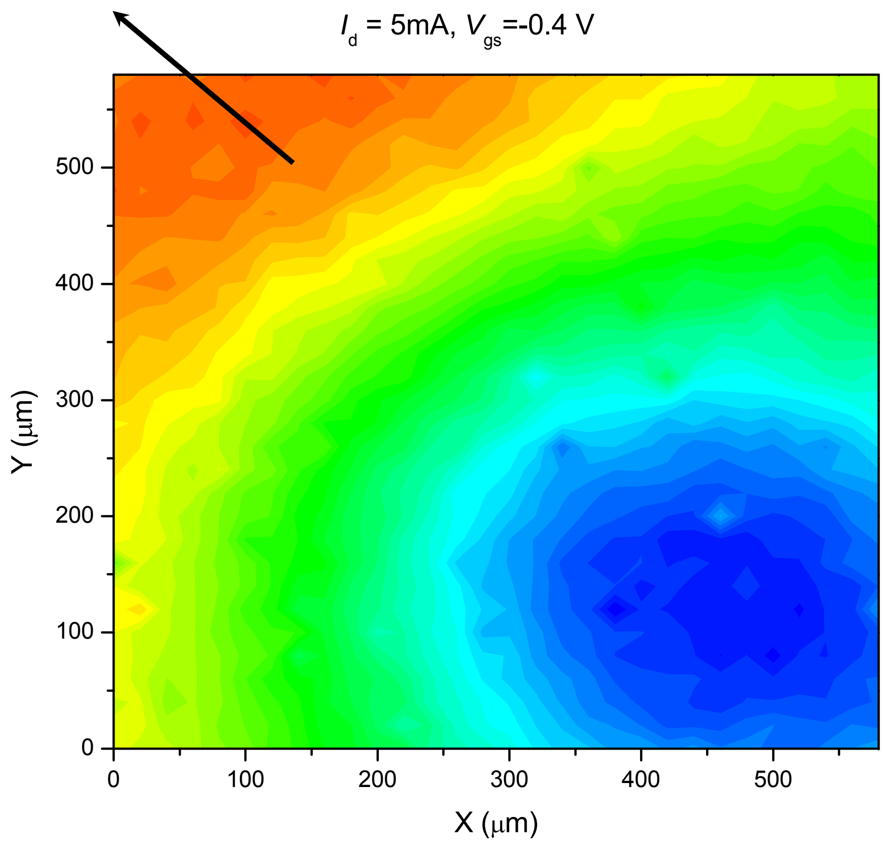
Sub-wavelength THz resolution is typically reached using a needle or sub-wavelength diaphragms and optically induced diaphragms

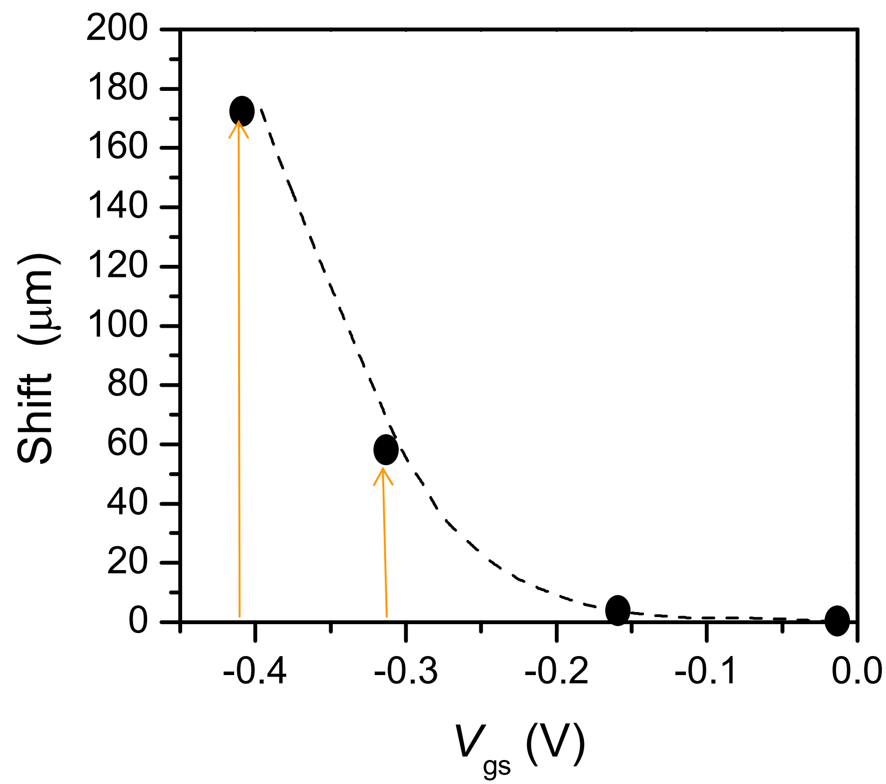
Here sub-wavelength resolution might be achieved due to variation of the responsivities driving the transistor with the drain current

Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Sub wavelength shift of sensitivity maximum

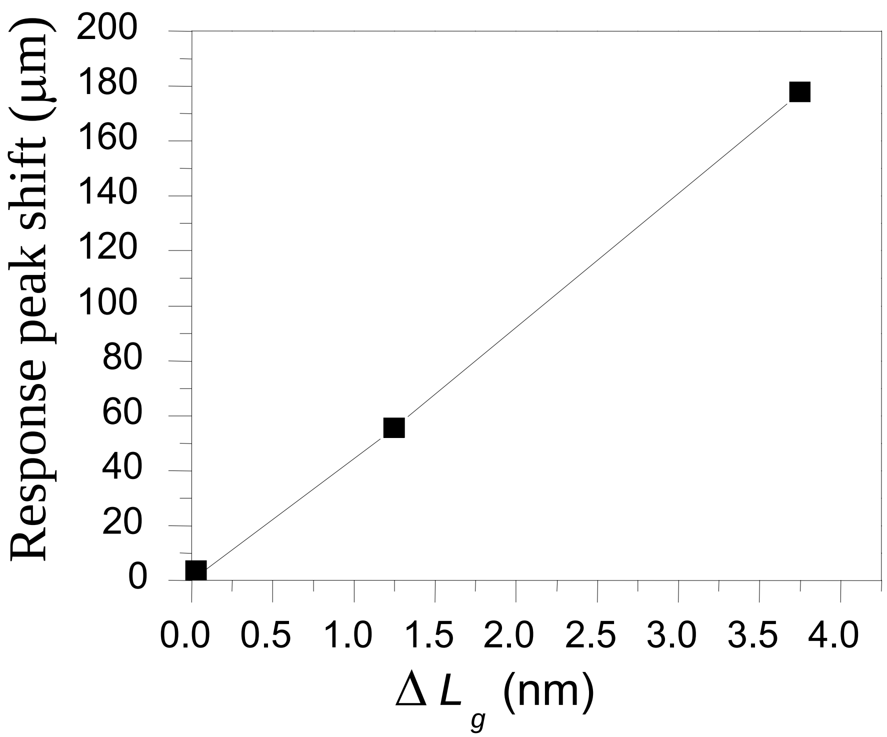
Driving transistor toward saturation regime we change ratio between positive and negative responses





Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Shift of the response maximum position vs. length of a high field region in the channel, ΔL_g.



- Plasmonic responsivity mechanism works as a magnifying glass: ~180 μm shift from nanometer scale change in the electric field distribution along the channel

- This dependence could be used as a calibration curve for determining the positions of the peak response as function of bias of FETs of different design

Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

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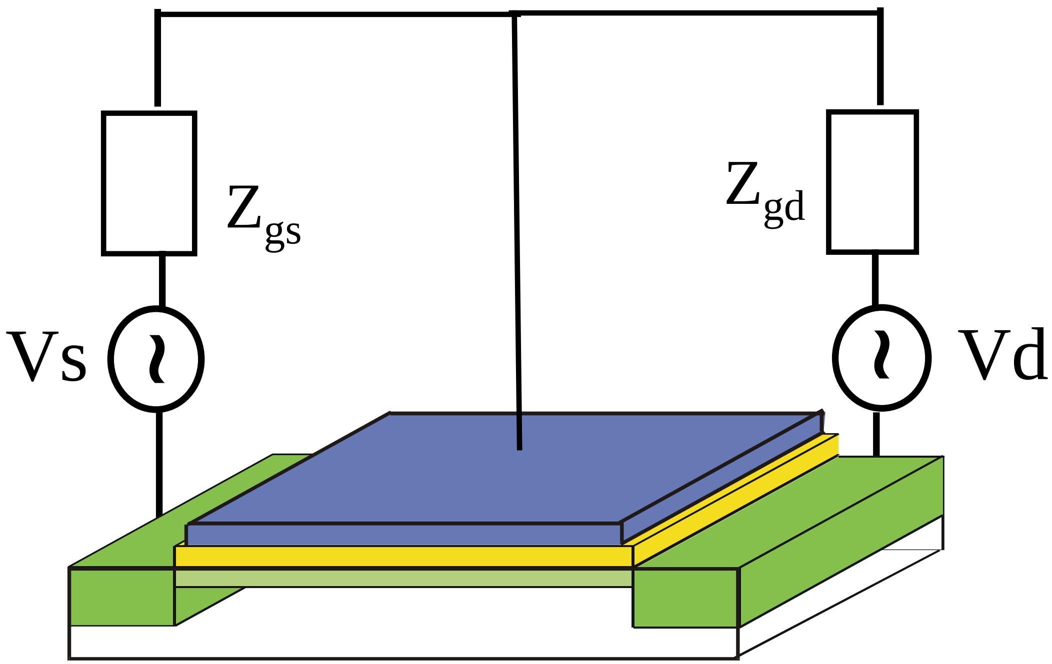
Interpretation



Vd and Vs are radiation induced AC voltages at source and drain sides of the channel

At I_d=0 sign of the signal depends on which AC source is stronger : Vd or Vs

At I_d>0 response signal caused by Vs increases while signal caused by Vs decreases accordingly

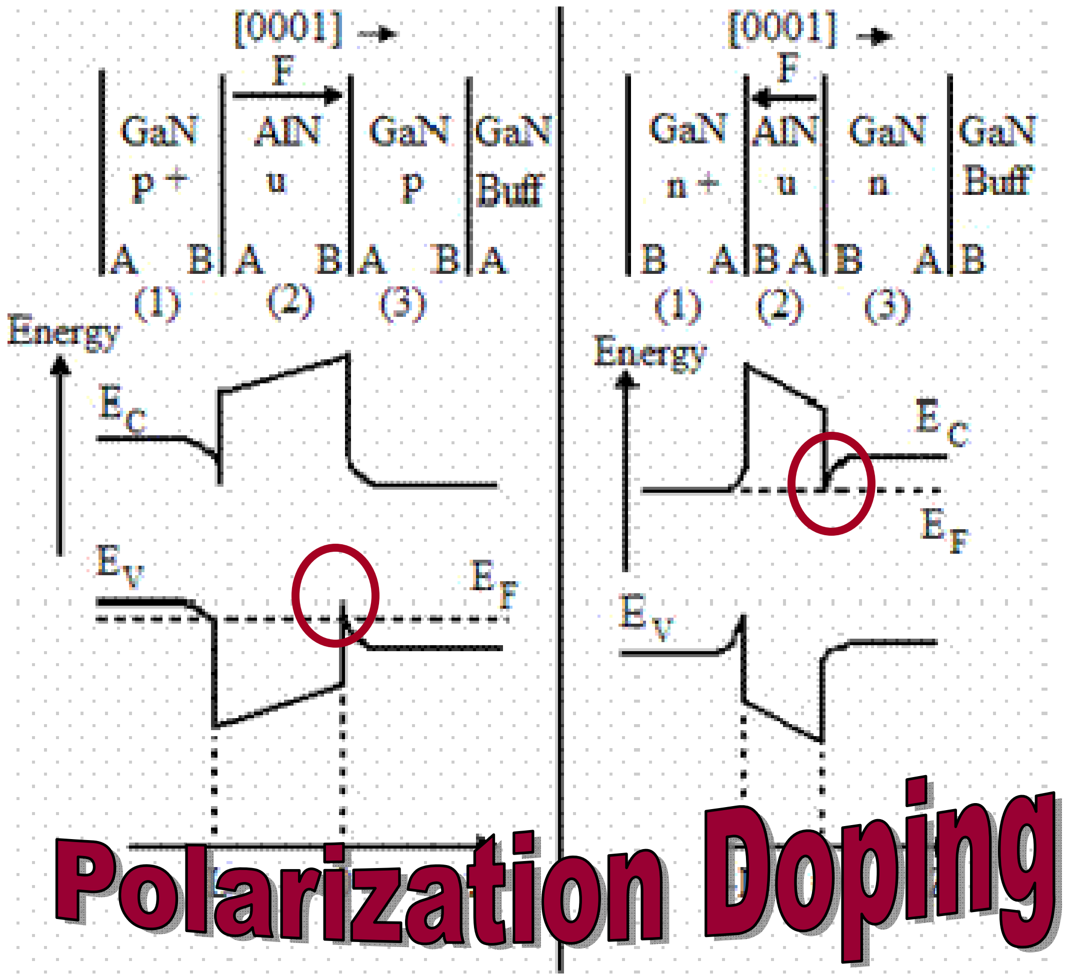
$$\delta U_0 = \frac{U_a^2}{4(U_{gs} - U_{th})(1 - j_d / j_{sat})^{1/2}}$$

Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Tutorial Outline

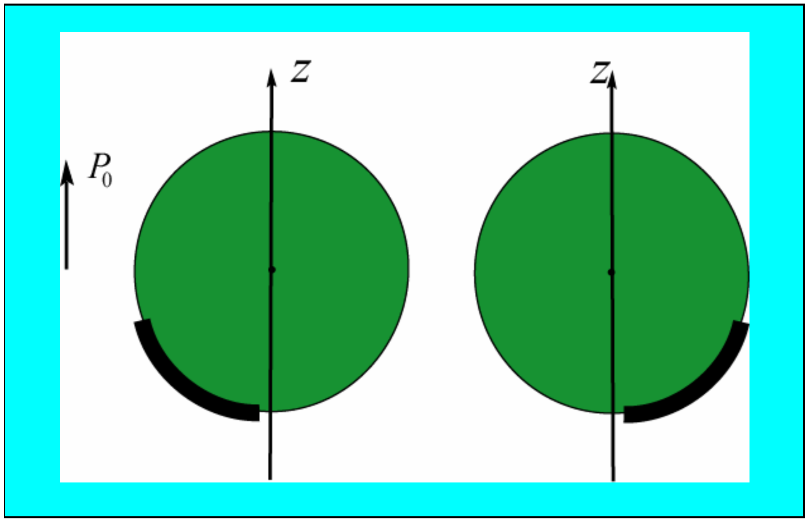
- History
- Application examples
- Terahertz Photonics
- Terahertz Electronics
- Plasma wave electronics
- **Terahertz properties of grainy multifunctional materials**
- Conclusions and future work

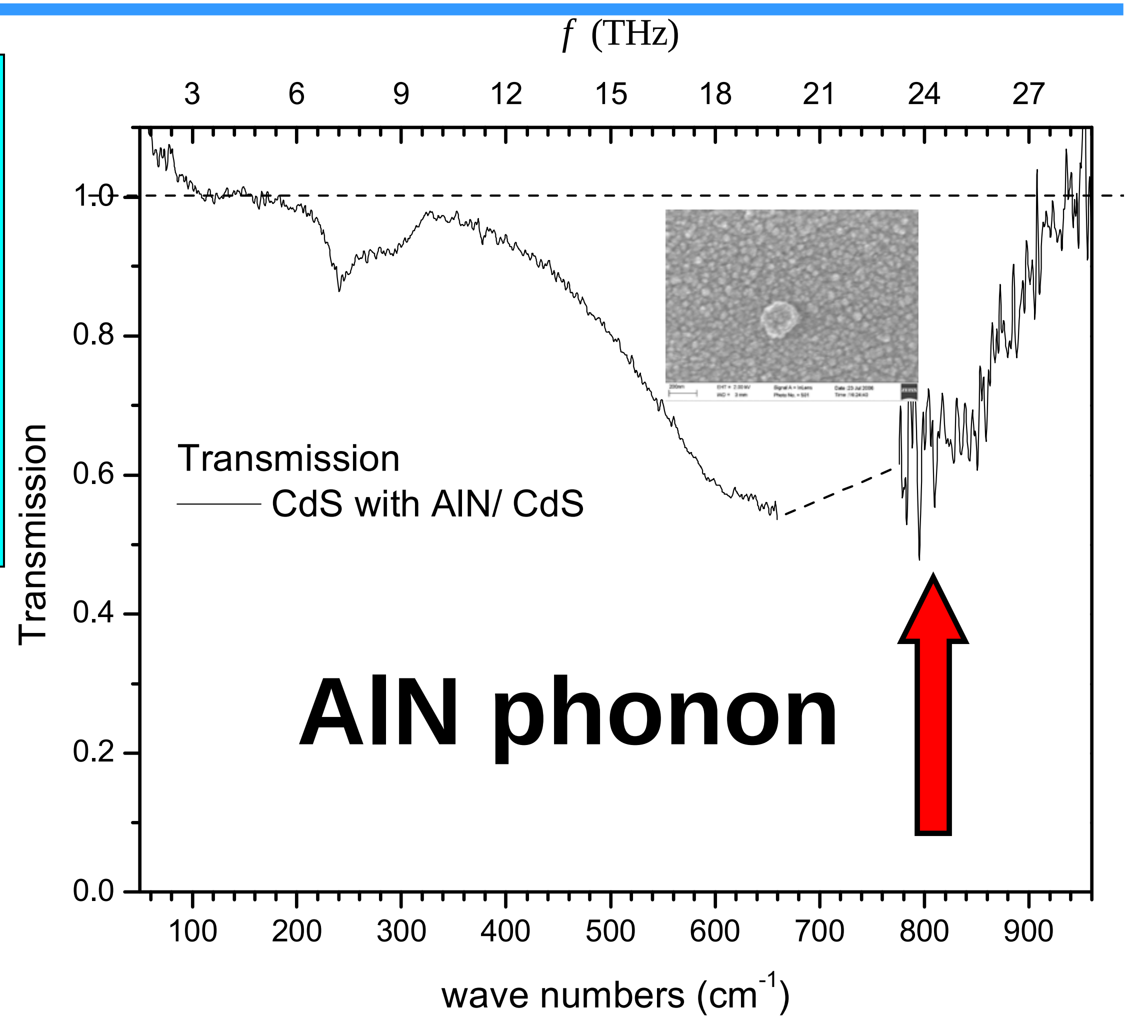
Polarization induced 2D electrons and holes in pyroelectric semiconductors



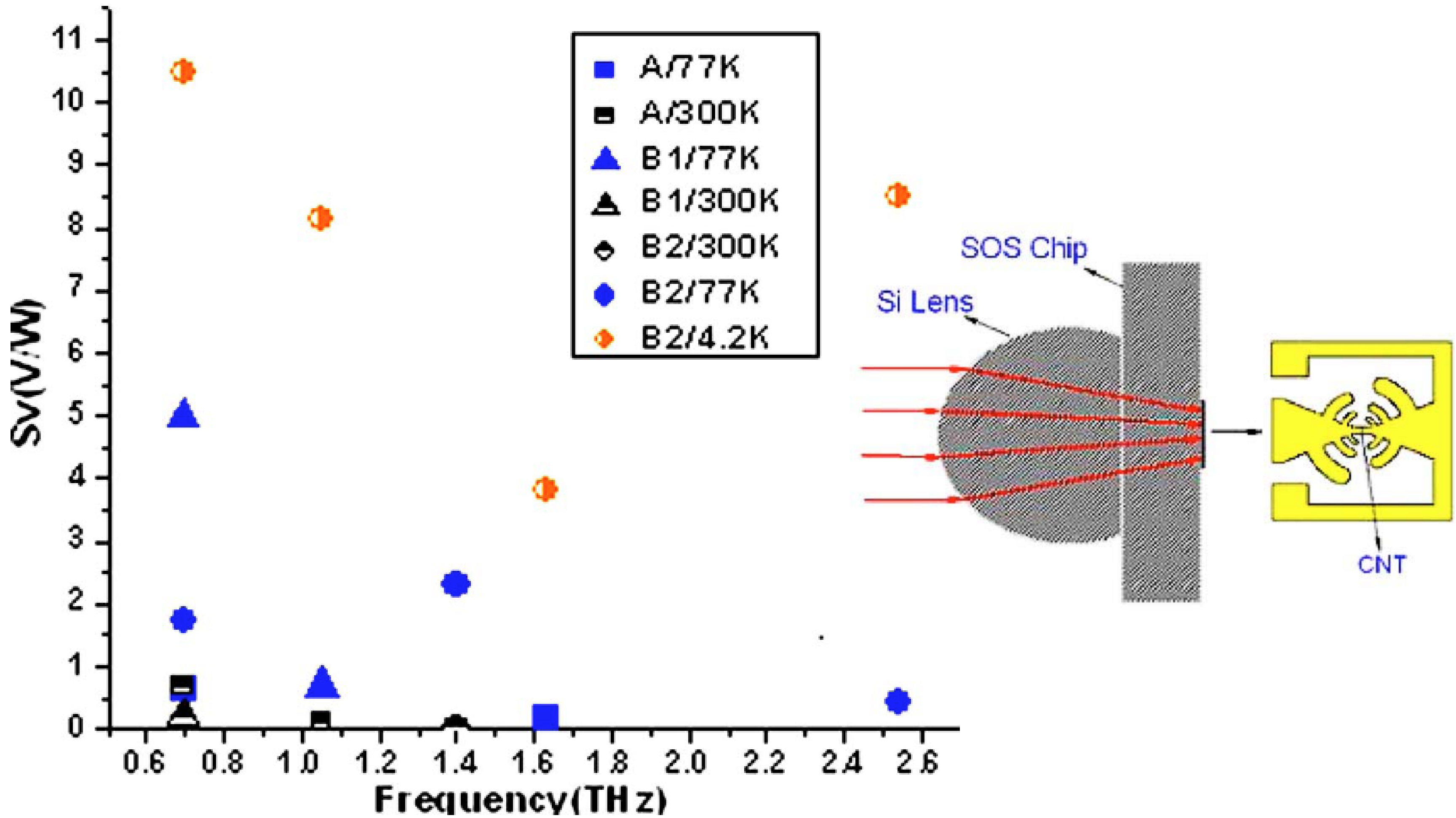
From A. Bykhovski, B. Gelmont, M. S. Shur J. App. Phys. Vol. 74 (11), p. 6734-6739 (1993)

THz Experiments in Progress



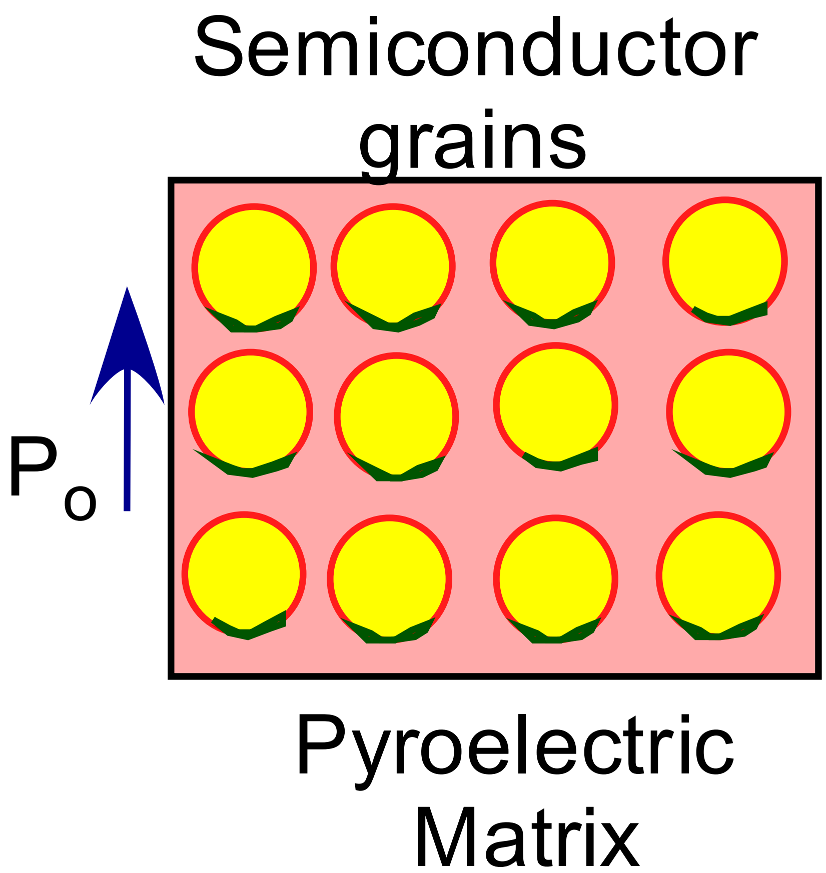


Responsivities of CNT terahertz detectors



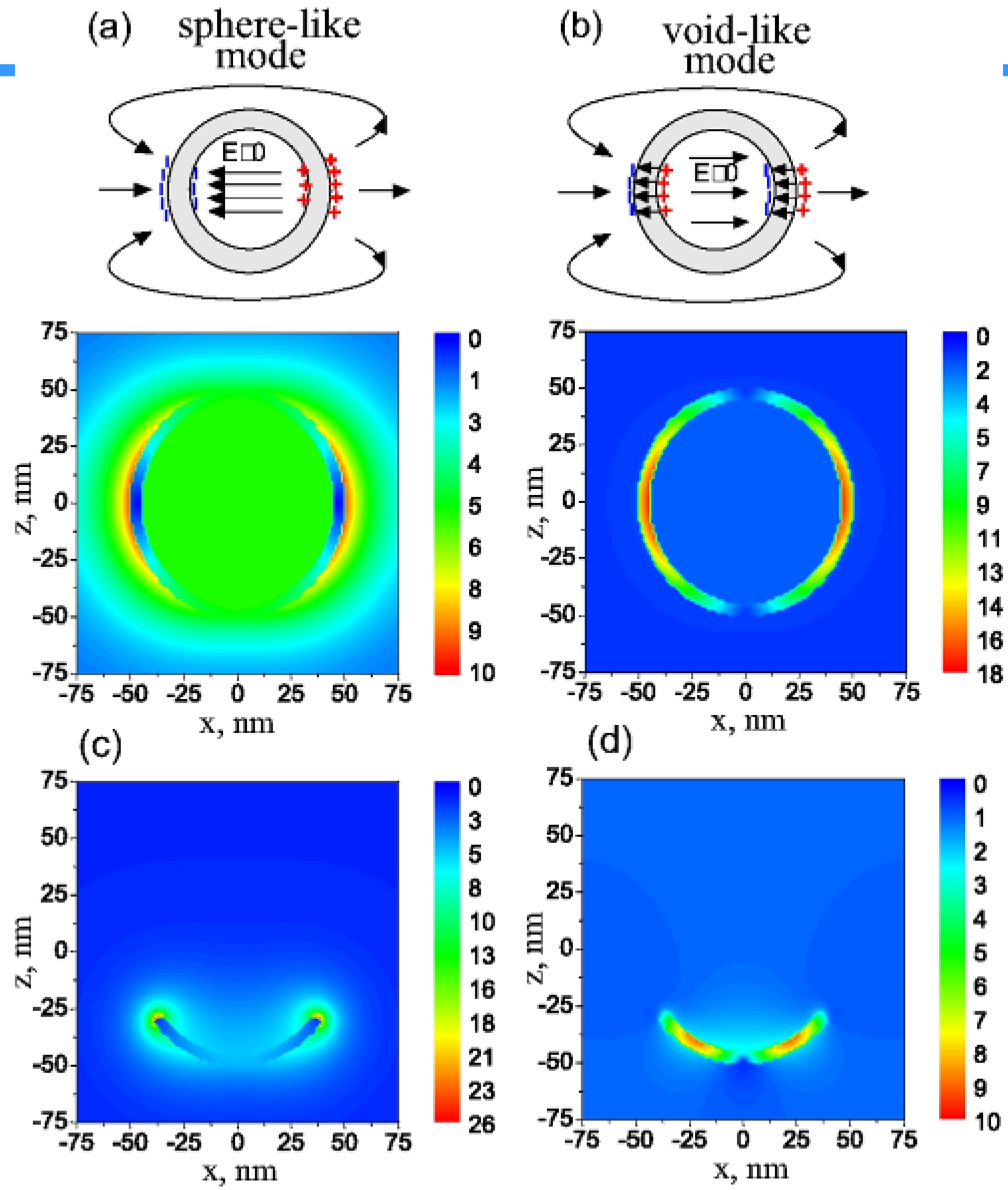
From Fu *et al.* Appl. Phys. Lett. 92, 033105 2008

Semiconductor Grains Forming Plasmonic Crystal



- 3D granular media, with semiconductor grains inserted in pyroelectric matrix can serve as uniaxial crystal operating in THz range of frequencies.
- The properties of this crystal can be easily tuned by external magnetic and electric fields and by optical excitation.

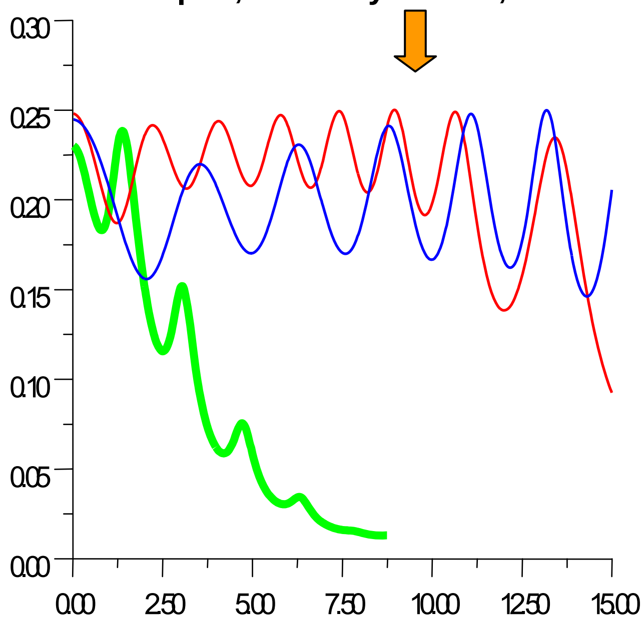
Field Distribution at resonances



From T. V. Teperik, F. J. Garcia de Abajo, V. V. Popov, and M. S. Shur, Strong terahertz absorption bands in a scaled plasmonic crystal, Appl. Phys. Lett. 90, 251910 (2007)

THz Array for Femtosecond Laser Excitation

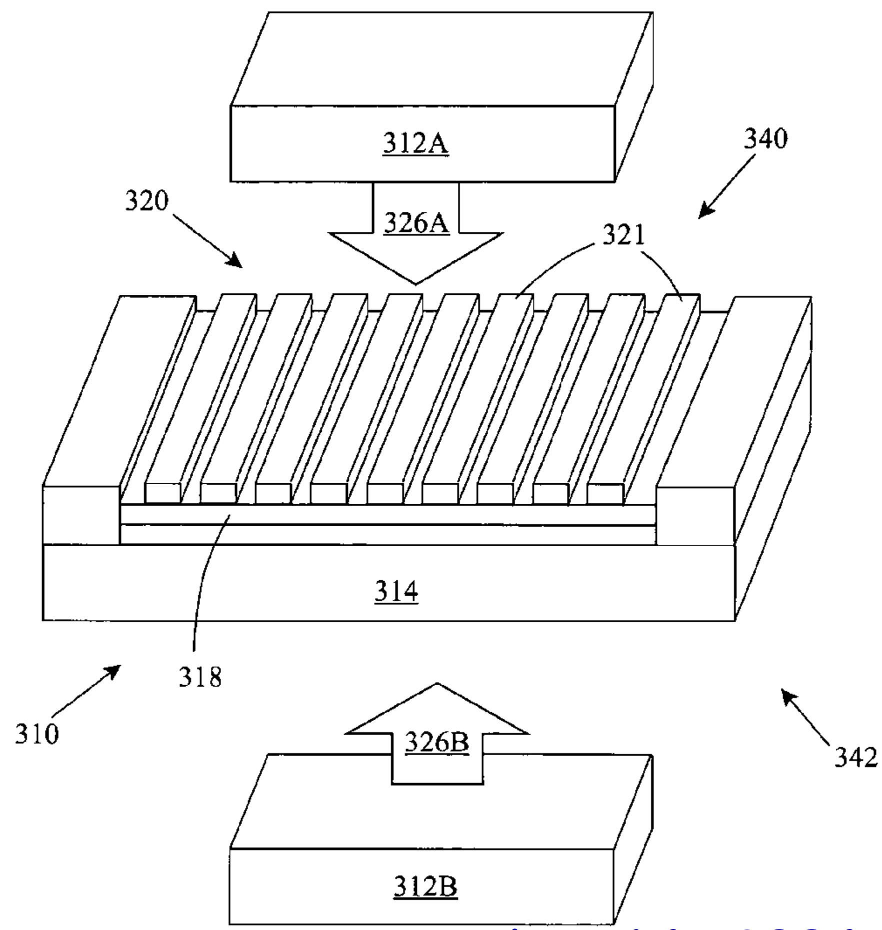
From . V.V. Popov, G.M. Tsymbalov, D.V. Fateev, M.S. Shur., Applied Physics Letters, 2006, Vol.89, No.12, P.123504/3



Patent Application Publication Oct. 14, 2004 Sheet 5 of 8 US 2004/0201076 A1

(54) METHOD OF RADIATION GENERATION AND MANIPULATION

(76) Inventors: **Michael Shur**, Latham, NY (US); **Victor Ryzhii**, Aizu-Wakamatsu City (JP); **Remigijus Gaska**, Columbia, SC (US)



October 14, 2004

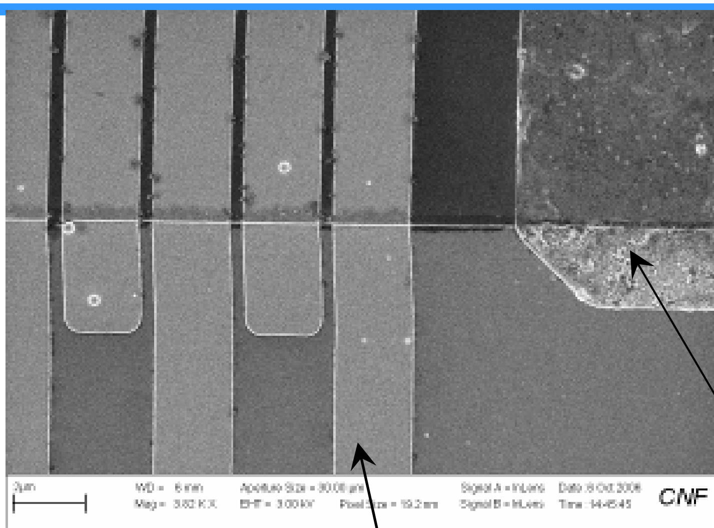
New physics of Movable Quantum Dots

- Self-assembled quantum dot arrays
- Coulomb blockade
- Light concentration in quantum dots
- Left handed materials (NIM)

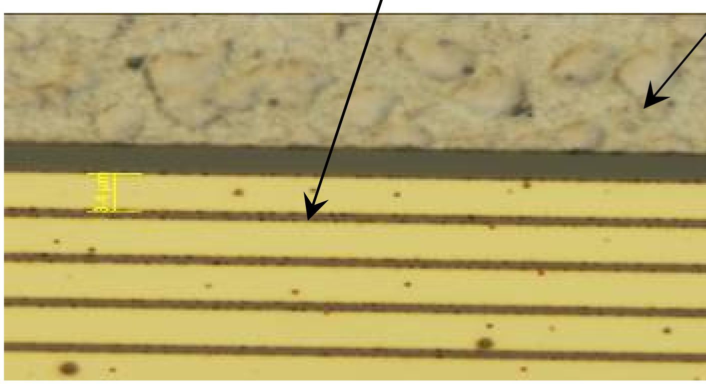
New Potential Applications

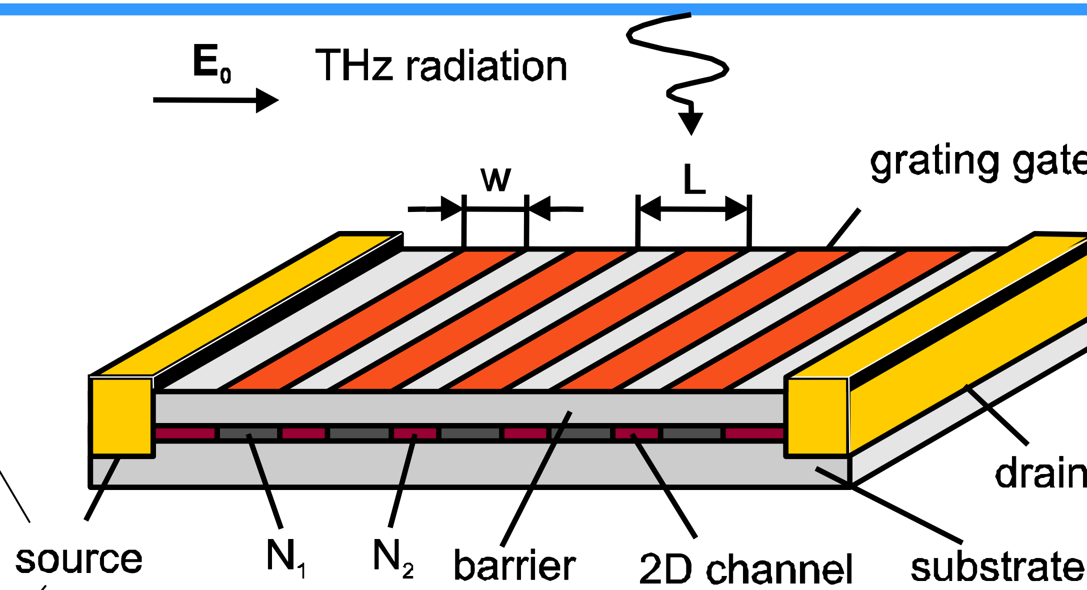
- Terahertz detectors
- Terahertz emitters
- Terahertz mixers
- Photonic terahertz devices
- Photonic crystals
- Plasmonic crystals
- Solar cells and thermovoltaic cells

HEMT Structure with Common Channel and Large Area Grating-Gate



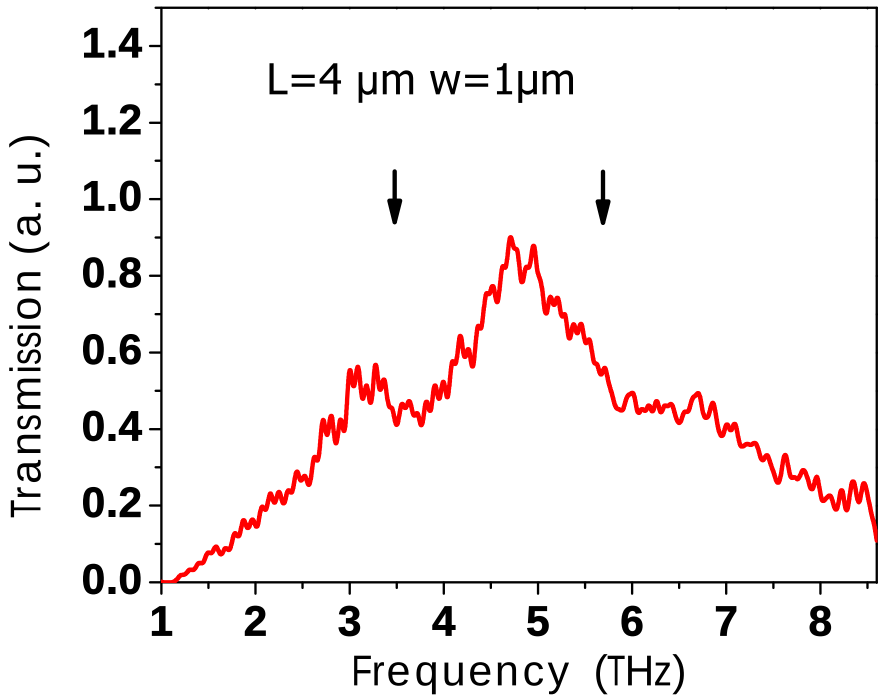
Grating Gate





From N. Pala, D. Veksler, A. Muravjov, W. Stillman, R. Gaska, and M. S. Shur, Resonant Detection and Modulation of Terahertz Radiation by 2DEG Plasmons in GaN Grating-Gate Structures, in Absracs of IEEE Sensors Conference, Atlanta, GA, October 2007

Measured Transmission Spectrum of Grating-gate FETs

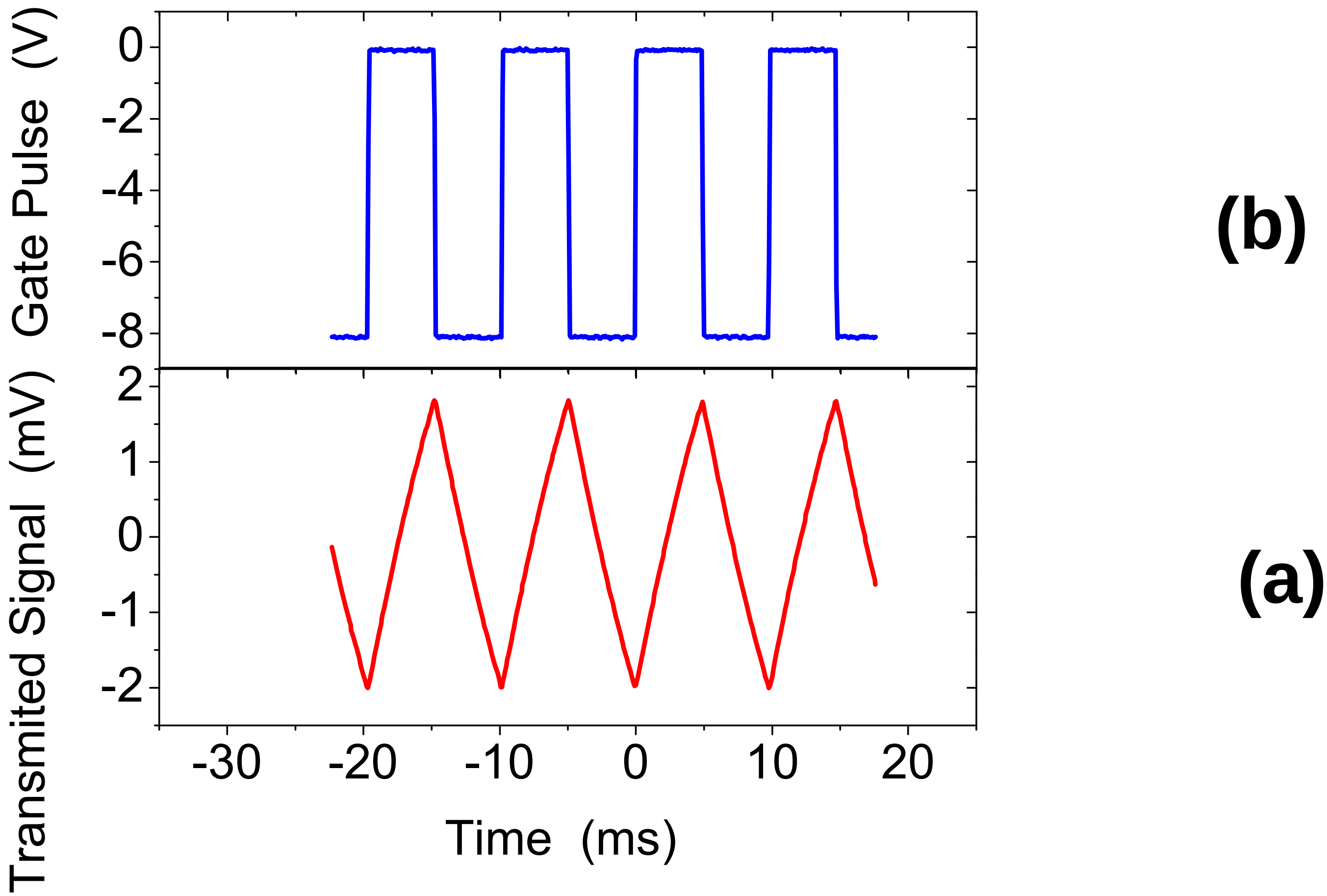


$$\omega_p = \sqrt{\frac{e^2 N_{2D}}{2\varepsilon\varepsilon_0 m} k}$$

Correct frequency ratio

From N. Pala, D. Veksler, A. Muravjov, W. Stillman, R. Gaska, and M. S. Shur, Resonant Detection and Modulation of Terahertz Radiation by 2DEG Plasmons in GaN Grating-Gate Structures, in Abstracts of IEEE Sensors Conference, Atlanta, GA, October 2007

THz signal (a) transmitted through grating gate biased by a pulsed signal (b)



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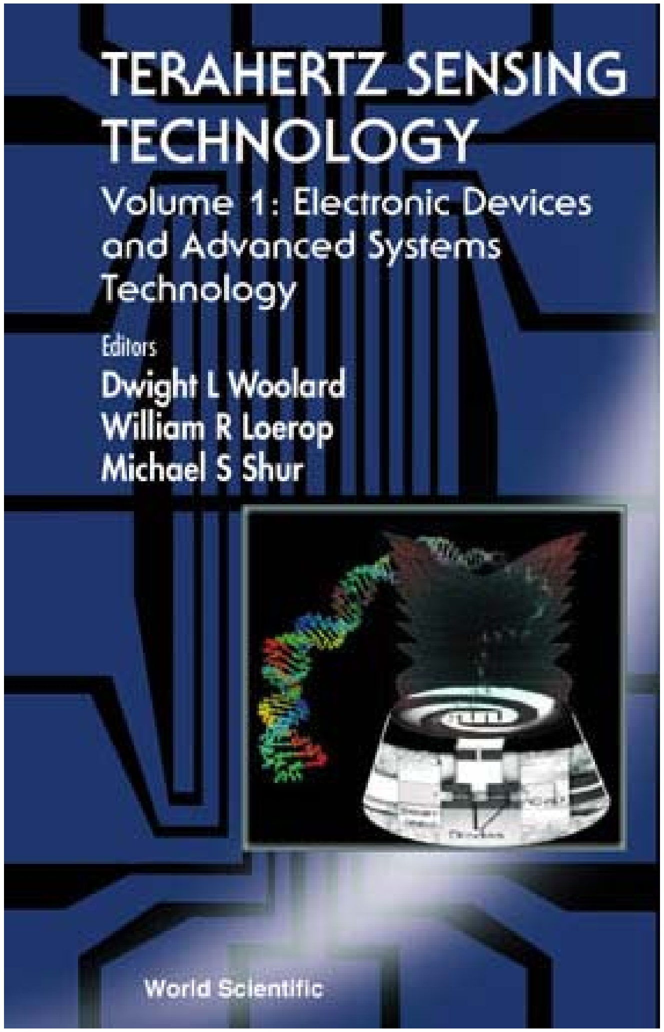
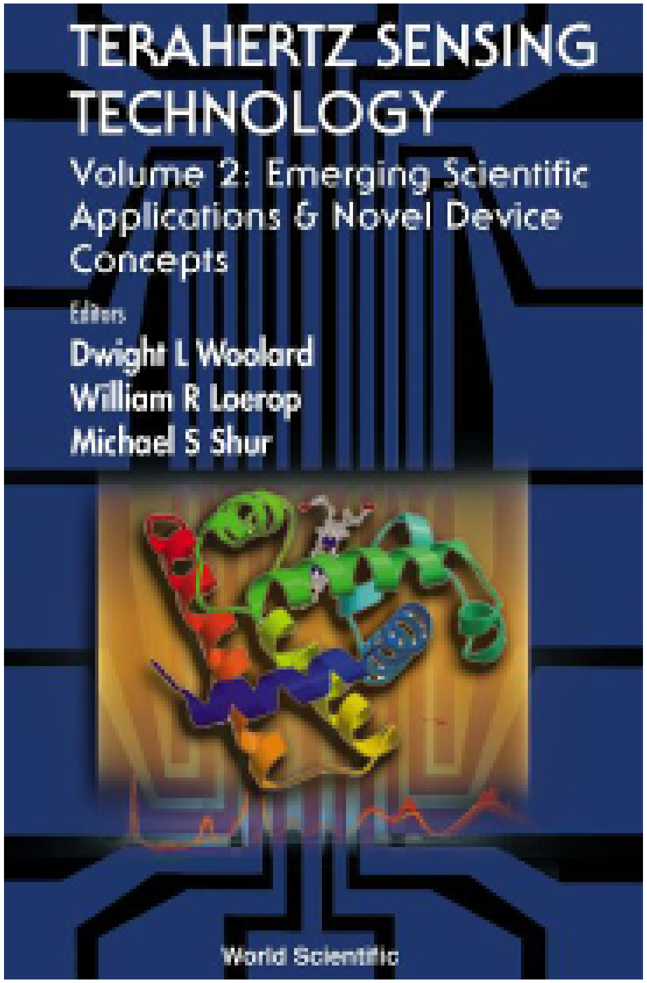
Conclusions

- Applications of THz technology are exploding
- Terahertz photonics: established technology but expensive and bulky
- Terahertz electronics: low powers, Schottky diode technology is mainstream, transistor technology is emerging
- Plasma wave electronics: resonant and non resonant detection in a wide temperature range in different materials systems; nanowatt sources with milliwatt potential
- Grainy multifunctional pyroelectric materials are predicted to form a new THz medium

To probe further





Hard Work But Steady Progress!

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